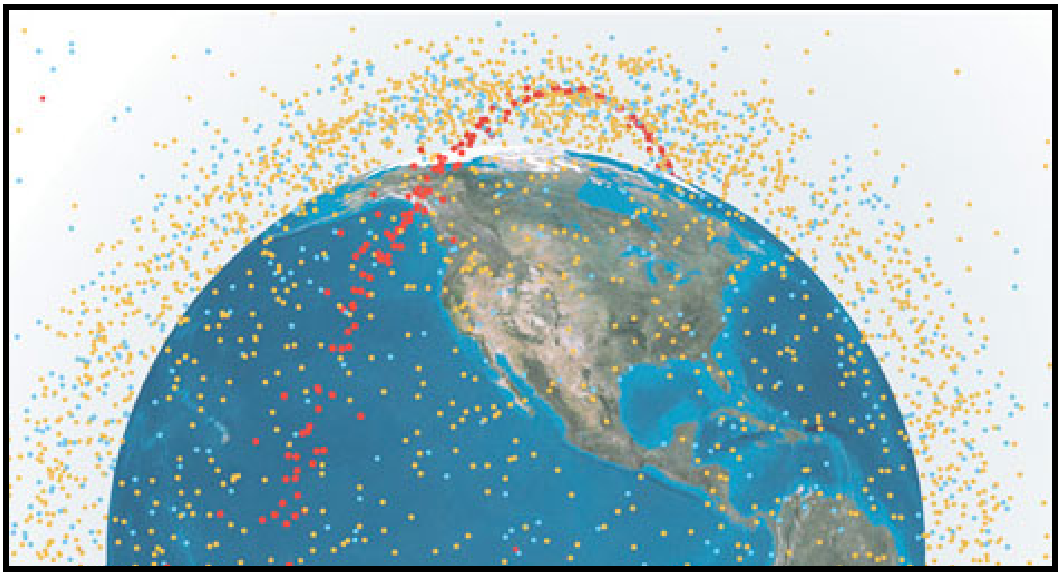
Global Innovation and Strategy Center

Eliminating Space Debris: Applied Technology and Policy Prescriptions

Fall 2007 – Project 07-02
January 2008



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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
JANUARY 2008	FINAL REPORT	SEPTEMBER 2007 - DECEMBER 2007

4. TITLE AND SUBTITLE
Eliminating Space Debris: Applied Technology and Policy Prescriptions

5a. CONTRACT NUMBER
N/A

5b. GRANT NUMBER
N/A

5c. PROGRAM ELEMENT NUMBER
N/A

6. AUTHOR(S)
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5d. PROJECT NUMBER
07-02

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
USSTRATCOM Global Innovation and Strategy Center (GISC)
Intern Program
6805 Pine Street
Omaha, NE 68106

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
USSTRATCOM Global Innovation and Strategy Center (GISC)
6805 Pine Street
Omaha, NE 68106

10. SPONSOR/MONITOR'S ACRONYM(S)
USSTRATCOM - GISC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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Within LEO's 2,000 kilometer altitude from earth's surface, tens of millions of pieces of space debris exist. While many larger pieces can be tracked and avoided, smaller pieces cannot. This "unseen threat" exemplifies the need for improvements in both space situational awareness and debris cataloguing. The space debris problem has been acknowledged by world bodies (United Nations) and global players alike (commercial interests and individual nation-states). Consequently, it can be argued that 50 years of space environmental utilization has brought clarity to space-faring entities.

15. SUBJECT TERMS
Space debris, lower earth orbit, LEO, ground-based laser, large area passive debris collector, Electrodynamic tethers, momentum tethers, rendezvous debris removal, drag augmentation device, space-based electromagnetic field generator

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	137	Dr. John G. Hudson II / 402-398-8034

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

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Preface

This report is the product of the Global Innovation and Strategy Center (GISC) Internship program. This program assembles combined teams of graduate and undergraduate students with the goal of providing a multidisciplinary, unclassified, non-military perspective on important Department of Defense issues.

The Fall 2007 team, composed of students from the University of Nebraska at Omaha, was charged with tackling the problems associated with orbital debris and remediation of the space environment. The lack of any existing elimination (clean-up) mechanism, combined with issues of domestic security, international policy and commercial interests, called for a multifaceted research approach. The financial and technological feasibility issues of outer space operations demanded a broad-based methodology.

This project took place between late August and December 2007, with each team member working ten to twenty hours per week. While the GISC provided the resources and technology for the project, it was solely up to the team to develop the project design, conduct research and analysis, and provide recommendations.

Acronyms

ABL	Airborne Laser
AEOS	Advanced Electro-Optical System
ASTRO	Autonomous Space Transfer and Robotic Orbiter
BBC	British Broadcasting Corporation
CDI	World Security Institute’s Center for Defense Information
CFE	Commercial and Foreign Entities
DOD	Department of Defense
EOL	End of Life
COPUOS	Committee on Peaceful Uses of Outer Space (United Nations)
DARPA	Defense Advanced Research Projects Agency
DART	Demonstration of Autonomous Rendezvous Technology
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FREND	Front-End Robotic Enabling Near-Term Demonstrations
ESA	European Space Agency
GBL	Ground-Based Laser
GEO	Geostationary Earth Orbit
GISC	Global Innovation and Strategy Center
GPS	Global Positioning System
IADC	Inter-Agency Space Debris Coordination Committee
ITU	International Telecommunications Union
ISS	International Space Station
LADC	Large Area Debris Collector
LDEF	Long Duration Exposure Facility
LEO	Lower Earth Orbit
LEGEND	LEO-to-GEO Environment Debris model
LLNL	Lawrence Livermore National Lab
MASTER	Meteoroid and Space Debris Terrestrial Environment Reference
MIT	Massachusetts Institute of Technology
MEO	Middle Earth Orbit
MSX	Mid-Course Space Experiment
NASA	National Aeronautics and Space Administration
NOAA	National Oceanographic and Atmospheric Administration
PMG	Plasma Motor/Generator
SBL	Space-Based Laser
SBSS	Space-Based Space Surveillance
SEDS	Small Expendable Deployment System
SIA	Satellite Industry Association
SSN	Space Surveillance Network
TiPS	Tether and Physics Survivability
UN	United Nations
USSTRATCOM	United States Strategic Command
XML	eXtensible Markup Language

Executive Summary

Communications, global commerce and national defense are today highly dependent on satellite constellations. This report details how space debris threatens valuable space-based technology essential to these critical areas. Traveling at speeds of over 7 kilometers per second,[1] a millimeter-sized particle could cause serious damage to equipment or death to a space explorer. Objects in lower earth orbit (LEO) pose the greatest immediate threat to space-based assets. This paper focuses on all sizes of debris found in LEO. What follows is a comprehensive analysis of the problem of space debris, specifically targeting policies that facilitate debris elimination.

Within LEO's 2,000 kilometer altitude from earth's surface, tens of millions of pieces of space debris exist. While many larger pieces can be tracked and avoided, millions of smaller pieces cannot. This "unseen threat" exemplifies the need for improvements in both space situational awareness and debris cataloguing.

Conversations with international space technology and policy experts reflect decades of intricate research and careful diplomacy. The space debris problem has been acknowledged by world bodies (United Nations) and global players alike (commercial interests and individual nation-states). Consequently, it can be argued that fifty years of space environmental utilization has brought clarity to space-faring entities.

The following points are noted:

[1]Primack, J. "Pelted by paint, downed by debris." Bulletin of the Atomic Scientists 58:5, Sept./Oct 2002. (27,000 kilometers per hour).

- Ground-based lasers currently offer the most efficient means for small debris remediation, but remain untested. A demonstration of ground-based laser technology under actual operating conditions is therefore of utmost priority.
- Electrodynamic tethers and orbital rendezvous vehicles promise great advancements in the de-orbiting, or graveyard propulsion, of large debris.
- United States domestic policy has made great strides towards a framework for “best practices” in debris prevention. The next logical step entails movement towards international “ownership” of a debris removal demonstration.
- The United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) in cooperation with the Inter-Agency Debris Coordination Committee (IADC) has formally acknowledged both the problem of space debris and the need for a platform for debris mitigation. Universal space definitions are lacking, however. When approved and codified, these would serve to clarify and enhance current space policy.
- Improvements to current information, integration, and data sharing practices are of vital universal concern.

Introduction

"Many objects have been jettisoned into space: lens covers, auxiliary motors, launch vehicle fairings, separation bolts used to lock fixtures in place…and objects merely dropped or discarded during manned missions."[2] That outer space exploration would create by-products is not surprising; every human venture in history has carried inefficiencies. While outer space seemed limitless a half-century ago, the Space Age has exemplified how quickly orbits around the Earth can be filled. Space debris has evolved from an environmental nuisance to a serious hazard; the U.S. space shuttle flies backwards and upside down to avoid the problem.[3] With tens of millions of debris fragments flying at high velocity through lower earth orbit, both human explorers and space hardware are vulnerable.

General Kevin P. Chilton, head of United States Strategic Command, recently wrote: "Military and civilian entities are heavily reliant on services that satellites provide, and space operations are so pervasive that it is impossible to imagine the U.S. functioning without them."[4] During *Operation Desert Storm*, commercial satellites provided 45% of all communications between the theater and the continental United States.[5] Today, according to General Chilton, "We rely on satellites to verify treaty compliance, monitor threats and provide advance warning of missile attacks. It's important to remember that

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[2] Mirmina, Steven A. "Reducing the Proliferation of Orbital Debris: Alternatives to a Legally Binding Instrument." The American Journal of International Law, 99:3 (2005): 649-662.
[3] Johnson, Nicholas. Space debris expert and United States IADC Representative. In-person interview, NASA Orbital Debris Office. 7 Nov. 2007. Houston, Texas.
[4] Chilton, Kevin P. "Securing Space." Los Angeles Times 04 Oct. 2007: Opinion. <http://www.latimes.com/news/opinion/la-oe-chilton4oct04,0,6082315.story?coll=la-opinion-rightrail.> Accessed Fall 2007.
[5] Cynamon, Charles H. "Protecting Commercial Space Systems: A Critical National Security Issue." Research Report, Air Command and Staff College, Air University. Maxwell AFB, Alabama, April 1999.

every soldier, sailor, Marine and airman in Iraq and Afghanistan relies on space technology for crucial advantages in the field."[6]

Commercially, the economy of the United States is heavily dependent on space assets in virtually every industry. Communications, Global Positioning System (GPS) technology, agriculture, weather monitoring, and shipment tracking in the manufacturing sector are all indispensable to workings of the market.[7, 8] With international economies interwoven across borders and cultures, damage to a critical satellite might pose serious monetary repercussions throughout multiple countries. For example, nearly a decade ago the failure of the Galaxy IV satellite rendered certain communications useless for two days. "The failure of that one satellite left about 80 (to) 90 percent of the 45 million pager customers in the United States without service…and 5400 of 7700 Chevron gas stations without pay-at-the-pump capability."[9]

U.S. News and World Report recently reviewed an exercise simulating a day in the life of the U.S. military without satellites; the deputy under secretary of the Air Force for space programs was questioned about the results. "Fundamentally, you go back to fighting a war like World War II where it's huge attrition rates, huge logistics, and huge expenses."[10] This example certainly speaks to the reliance on space assets. A lack of action to secure space assets might prove even costlier.

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[6] Chilton, Kevin P. "Securing Space." Los Angeles Times 04 Oct. 2007: Opinion. <http://www.latimes.com/news/opinion/la-oe-chilton4oct04,0,6082315.story?coll=la-opinion-rightrail.> Accessed Fall 2007.
[7] Ibid.
[8] Cynamon, Charles H. "Protecting Commercial Space Systems: A Critical National Security Issue." Research Report, Air Command and Staff College, Air University. Maxwell AFB, Alabama, April 1999.
[9] Ibid.
[10] Whitelaw, Kevin. "China Aims High: Beijing's blast sets off a debate about how to protect U.S. satellites." U.S. News and World Report 17 Dec. 2007. <http://www.usnews.com/articles/news/2007/12/04/china-aims-high.html>. Accessed Dec. 2007.

In a knowledge-based, information-driven economy, the ability to communicate effectively and quickly is sacrosanct. *The Economist* recently painted the determination of the outcomes of future conflicts as a matter of "Brains, Not Bullets."[11] If information superiority is today's manifest destiny, the security of space assets is not optional.

History of Debris

> It has seriously been suggested that an anti-litter ordinance be adopted providing that after a satellite's radio has gone dead and its usefulness served, a small rocket will push the satellite toward earth, there to be consumed in the atmosphere. Otherwise, it is argued, space will soon be littered with hundreds of satellites, impossible to keep track of, and representing a hazard to navigation.[12]
>
> \- *Foreign Affairs*, October 1958

The first known break-up of an artificial satellite occurred in June 1961, when America's *Transit 4-A* exploded, producing 294 trackable pieces of debris.[13] Sixteen months later, the SL-6 upper stage booster from *Sputnik 29* exploded, producing 24 pieces of trackable debris, though none remained in orbit.[14] In 1964, the launch of *U.S. Transit 5BN3* satellite failed, resulting in a scattering of radioactive materials over the Indian Ocean.[15]

Twenty years and two thousand launches later, these early numbers seem insignificant. By 1984, 5,921 objects circled the planet, yet only 2,645 satellites had

[11] "Brains, Not Bullets: How to Fight Future Wars." The Economist. Oct. 2007: Front cover.
[12] Quigg, Phillip W. "Open Skies and Open Space." Foreign Affairs 37:1 (1958): 95-106.
[13] Portree, David S. and Joseph P. Loftus Jr. "Orbital Debris: A Chronology." The NASA Scientific and Technical Information Program Office. Jan. 1999.
[14] Portree and Loftus, 1999.
[15] Ibid.

successfully reached or transcended Earth's orbit; a ratio greater than 2:1.[16] That same year, NASA began examining effects of the orbital environment by the launching of the Long Duration Exposure Facility (LDEF) (Appendix A).[17]

Designed to provide data on the space environment and its effect on space operations over the long-term, the nearly six-year voyage of the LDEF provided a vast amount of crucial debris information when retrieved in 1990:

> Detailed inspections of LDEF surfaces…have resulted in an excellent benchmark data set of craters resulting from hypervelocity impacts of both natural meteoroids and man-made orbiting debris….LDEF exposed most of the materials (to the space environment) that are of interest to spacecraft designers…from 6061-T6 aluminum, other metals, polymers, composites, ceramics and glasses.[18]

The use of multiple surface types on the LDEF proved a powerful diagnostic tool. Upon post-retrieval examination, more than 4,000 visible impacts were initially noted, ranging in size from three-tenths of a millimeter to 5 millimeters; eventually over 15,000 smaller impact features would be documented.[19] The National Research Council confirmed the value of space environmental knowledge garnered by the LDEF, reporting

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[16] Ibid.
[17] Long Duration Exposure Facility Archive System. NASA Langley Research Center, Hampton Virginia. 29 Oct. 2007. <http://setas-www.larc.nasa.gov/LDEF/index.html>. Accessed Fall 2007.
[18] "Meteoroid and Debris Environment." 04 April 2001. Long Duration Exposure Facility Archive System, NASA Langley Research Center, Hampton Virginia. <http://setaswww.larc.nasa.gov/LDEF/MET_DEB/md_enviro.html>. Accessed Fall 2007.
[19] "Impact Damage of LDEF Surfaces." Long Duration Exposure Facility Archive System, NASA Langley Research Center, Hampton, Virginia.<http://setas-www.larc.nasa.gov/LDEF/MET_DEB/md_impact.html.> Accessed Fall 2007.

"Most debris experts were surprised when LDEF data suggested the existence of a significant population of small debris."[20]

Such knowledge is reflected in the design of high-value missions such as the International Space Station (ISS).[21] Hailed as a "great international, technological, and political achievement," the ISS was designed to withstand debris damage by the shielding of high-impact risk areas (Appendix B).[22, 23] NASA Chief Scientist Dr. Nicholas Johnson noted the "considerable effort and cost for reasons of human protection" that went into the design and building of the ISS countered that of non-human facilities: "No robotic spacecraft has as much cost input as the ISS for human protection."[24]

The global construction effort of the ISS presents a catalyst for worldwide dialogue; the international politics of space debris are nearly as complicated as space itself. The advent of ocean-based launching by international conglomerate *Sea Launch* in 1995 exemplified these complications[25] as reflected in a UN news report:

> The consortium is registered in the Cayman Islands and consists of four partners: Norwegians, Russians, Ukrainians…and the American company *Boeing*…the ship and platform used…are registered in Liberia. What is a failed launch

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[20] National Research Council. Orbital Debris: A Technical Assessment. National Academy Press, Washington, D.C. (1995).
[21] Ibid.
[22] NASA Reference Guide to the International Space Station. 19 Jan. 2007. <http://www.spaceref.com/news/viewsr.html?pid=23098>. Accessed Fall 2007.
[23] National Aeronautics and Space Administration Orbital Debris Program Office. "Orbital Debris Education Package: To Whom is the Information Important? International Space Station." <http://orbitaldebris.jsc.nasa.gov/library/EducationPackage.pdf>. Accessed Fall 2007.
[24] Johnson, Nicholas. Interview via conference call. 18 Sept. 2007.
[25] "Sea Launch, Cruising to Orbit: History." Sea Launch Company LLC, History web page. <http://www.boeing.com/special/sea-launch/history.htm> Accessed Fall 2007.

accidently drops a rocket on a fifth country? Which government will be held responsible?[26]

Pointedly, the same report quoted a German aerospace lawyer in reference to the 1996 collision between France's communication satellite *Cerise* and debris from the country's own *Ariane I* rocket body,[27] "Just imagine if that debris had come from a Russian or Chinese launcher."[28]

Space Debris

The Hazard

Millions of tiny space debris particles orbit the earth today, some travelling ten times faster than a high-powered rifle bullet.[29] [30] According to NASA scientist and space debris expert Dr. Nicholas Johnson, millimeter fragmentations are a greater threat than larger objects like defunct satellites as they are too small to be tracked with current technology.[31] The estimated 11,000 objects large enough to be tracked are catalogued

[26] Otchet, Amy. "Space law lifts off for a new odyssey: 3rd UN Conference on the Exploration and Peaceful Uses of Outer Space." United Nations Educational, Scientific and Cultural Organization (UNESCO) Courier. June 1999.
[27] National Aeronautics and Space Administration Orbital Debris Program Office. "Orbital Debris Education Package: Cerise Collision (accidental)." <http://orbitaldebris.jsc.nasa.gov/index.html>. Accessed Fall 2007.
[28] Otchet, Amy. "Space law lifts off for a new odyssey: 3rd UN Conference on the Exploration and Peaceful Uses of Outer Space." United Nations Educational, Scientific and Cultural Organization (UNESCO) Courier. June 1999.
[29] National Aeronautics and Space Administration Orbital Debris Program Office. "Frequently Asked Questions." <http://orbitaldebris.jsc.nasa.gov/faqs.html>. Accessed Oct. 2007.
[30] Primack, J. "Pelted by paint, downed by debris." Bulletin of the Atomic Scientists 58:5, Sept./Oct 2002.
[31] Johnson, Nicholas. Interview via conference call. 18 Sept. 2007.

and monitored, enabling satellite operators to maneuver around them by expending additional fuel.[32]

When small debris pieces collide with space assets, the result is not simply a matter of speed, but also of motion. “Because the (low earth orbit) velocities are so high, the kinetic energy is very high. It’s the equivalent of exploding several sticks of dynamite in your spacecraft,” noted a BBC report on the problem.[33] Debris fragments as small as one-tenth of one millimeter could potentially puncture the suit of an astronaut.[34] The “Kessler effect”[35] complicates matters further: as the volume of satellites increases, so does the probability that they will collide with each other.[36] Such a chain reaction is “inevitable,” according to Dr. Nicholas Johnson[37] in an interview with *The New York Times*, “A significant piece of debris will run into an old rocket body, and that will create more debris. It’s a bad situation.” In summary, while preventative measures against debris creation are vital, they will not prevent further growth arising from existing debris.

Debris Origins

Space debris is a result of explosions, collisions or decay of space missions in Earth's orbit. Debris is commonly categorized in terms of small debris (diameter less than

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[32] National Aeronautics and Space Administration Orbital Debris Program Office. “Orbital Debris Education Package: How Much Orbital Debris is Out There and how do we avoid being hit by it?” <http://orbitaldebris.jsc.nasa.gov/index.html>. Accessed Nov. 2007.

[33] Fry, Carolyn. "C02 prolongs life of 'space junk'." BBC News. 05 May 2005. <http://news.bbc.co.uk/1/hi/sci/tech/4486049.stm.> Accessed Fall 2007.

[34] Mirmina, Steven A. “Reducing the Proliferation of Orbital Debris: Alternatives to a Legally Binding Instrument.” The American Journal of International Law, 99:3 (2005): 649-662.

[35] Hatfield, Larry D. "Mir Space Junk." San Francisco Chronicle. 23 Mar. 2001: A1.

[36] Kessler, Donald J. and Burton G. Cour-Palais. “Collision Frequency of Artificial Satellites: The Creation of a Debris Belt.” Journal of Geophysical Research, 83:A6. 1978.

[37] Broad, William J. “Orbiting Junk, Once a Nuisance, Is Now a Threat." New York Times. 6 Feb. 2007. <http://www.nytimes.com/2007/02/06/science/space/06orbi.html.>. Accessed Fall 2007.

10 cm) and large debris (diameter greater than 10 cm). The total debris count exceeds 10,000 for large debris, while small debris numbers in the millions.[38]

Debris 10 cm or larger tracked by the Space Surveillance Network (SSN):
37.7% breakups
31.3% payloads
16.6% rocket bodies
13.0% mission-related
1.3% anomalous debris

The amount of debris cause by the breakups can be defined further:

45.7% propulsion
31.2% deliberate
17.9% unknown
4.6% battery
0.6% collision

These numbers are all from the 13th edition of the breakup book released by NASA in May of 2004.[39] In early 2007 there were major breakup events that caused a significant increase in the number debris.

Debris Detection and Tracking

Space debris can be detected to a very small size using various methods. When a piece of debris is detected, its trajectory can be calculated using the "stare and chase" method. The object of this methodology is to use radar to successfully identify, track, and project trajectories of objects. Debris tracking involves constant monitoring of the debris

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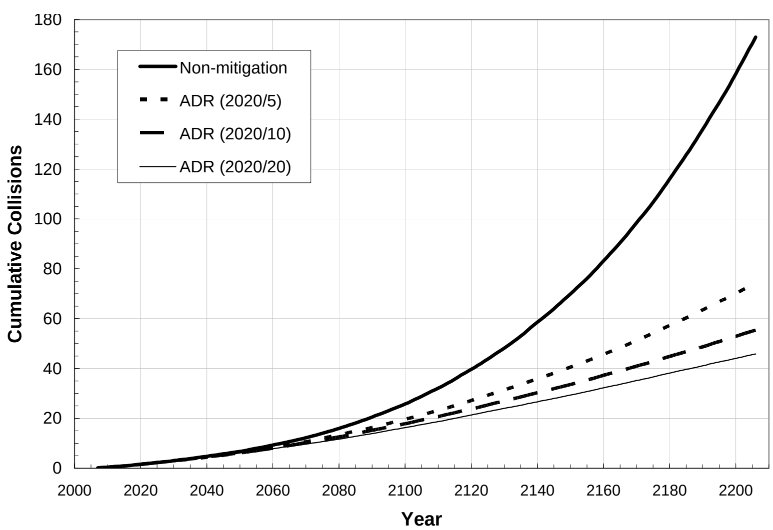
[38] National Aeronautics and Space Administration Orbital Debris Program Office. "Frequently Asked Questions." <http://orbitaldebris.jsc.nasa.gov/faqs.html>. Accessed Oct. 2007.
[39] Whitlock, David O. and Jer-Chyi Liou. History of On-Orbit Satellite Fragmentations, 13th Ed. May 2004. National Aeronautics and Space Administration Orbital Debris Program Office.<http://orbitaldebris.jsc.nasa.gov/library/SatelliteFragHistory/13thEditionofBreakupBook.pdf>. Accessed Fall 2007.

using a network of various observation techniques. Objects larger than 10 cm can be tracked. About 7,000 objects greater then 10 cm in size are currently being tracked.

Large Debris Collision Forecast

NASA Scientist Dr. Nicholas Johnson has projected the growth of debris over time if no mitigation action is taken. In addition, he has used the data is to forecast the impact of debris mitigation efforts beginning in the year 2020 and assuming that 5, 10, and 20 pieces of debris are eliminated yearly beginning 2020. Based on this data, Figure 1 portrays the estimated numbers of anticipated collisions by year based on varied levels of mitigation. The top, solid line (thickest) shows projected collision numbers if no mitigation effort is made. Although the number does not seem too alarming at first, eventually expected collisions begin to rise exponentially. However, if a significant effort is made to remove debris, even though space activity increases dramatically, the risk of collision remains virtually the same as current levels.



Non-mitigation (no action taken)
------- 5 objects removed annually beginning in 2020
— — 10 objects removed annually beginning in 2020
—— 20 objects removed annually beginning in 2020

Figure 1: Projected Collisions

Analysis

If the orbital debris population remained as it is today with no additional space operations, the level of fragmentation in Earth's orbit would continue to escalate exponentially. Dr. Nicholas Johnson, chief scientist for orbital debris for NASA at the Johnson Space Center, has modeled future orbital debris scenarios based on non-mitigation over a 5, 10, and 20 year period compared to the removal of one to five pieces of debris beginning in the year 2020. This paper, co-authored by J.-C. Liou and titled "A Sensitivity Study of the Effectiveness of Active Debris Removal in LEO," suggests that the orbital debris population can be effectively addressed by simply removing five objects per year starting in the year 2020.

Orbits

Lower Earth Orbit (LEO)

Lower Earth Orbit (LEO) is approximately 200 to 2000 kilometers in altitude. LEO is of particular concern because of the high density of space assets and the speeds at which collisions can occur. Collisions can happen at speeds of approximately 15 km/s. At this speed, debris as small as one centimeter in diameter contains enough kinetic energy to destroy a satellite. Laboratory tests show that these catastrophic collisions can create 10^8 to 10^{10} pieces of debris.[40]

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[40] Hanada, T, Y. Tsuruda, and J.-C. Liou. "New Satellite Impact Experiments." Orbital Debris Quarterly News 10:3. July 2006. <http://www.orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv10i3.pdf>. Accessed Fall 2007.

Geostationary Earth Orbit (GEO)

Geostationary Earth Orbit (GEO) is approximately 35,000 km in altitude. GEO is less populated and collisions occur at 10 to 100 m/s. However, decay time for GEO is measured in centuries, orders of magnitude higher than in LEO. Debris does not naturally decay in a timely manner in this orbit.

Orbital Velocities

Orbital velocities can be defined as the velocity of an orbiting body at a specified altitude. Each altitude above the earth's surface has a corresponding orbital velocity associated with it. For example, a body orbiting at 200 km will move at approximately 7.78 km/second. If a collision were to occur at an altitude of 200 km, the maximum velocity that would be experienced on both orbiting bodies involved in the collision would be double 7.78 km/second or 15.56 km/second. The collision velocity would be double the orbital velocity if the two orbiting bodies are traveling in opposing orbits.

Every orbiting body is experiencing a gravitational force exerted on it by the earth. This force places orbiting bodies in a spiral orbit towards the earth at a fixed rate based on the object's mass. The shape and orientation of an orbiting body will also contribute to its orbital velocity. If an orbiting body has a large surface area and its face is oriented in the direction of motion, its orbital velocity can be significantly changed because of atmospheric drag.

Objects orbiting the earth only have a measurable instantaneous velocity as its velocity will always be changing with time. For a satellite to maintain a specified orbit, it must periodically adjust its velocity to compensate for the gravitational force applied to it from the earth. The frequency of required adjustments are dependant on the orbiting

object's altitude. More adjustments are needed at lower altitudes because the earth's gravitational field is stronger closer to the surface.

Major Increases to the Debris Population: 2007 Orbital Debris Events

Anti-satellite Missile Test (China)

> You can pollute a stream or an ocean for a long time and not see any consequence…by the time you see something, it may be very difficult or very costly to remedy the environment.
>
> – Dr. Nicholas Johnson, NASA

Two major events in the first quarter of 2007 caused concern within the international space exploration community and are briefly described here.

On January 11, 2007, the Chinese government used an anti-satellite missile to destroy an aging but still active weather satellite. By all accounts, the collision between the anti-satellite missile and the FC-1 weather satellite caused the satellite to burst into thousands of fragments that scattered into the atmosphere within an hour of the "test." Chinese officials did not acknowledge or confirm the test until January 22, 2007.

International opinion was critical of the test due to the significant amount of debris that resulted. The United States was aware of two prior anti-satellite weapon tests (ASAT) by the Chinese on July 7, 2005 and February 6, 2006. In both prior instances, the U.S. did not file diplomatic protests either bilaterally or in a multilateral forum.

Breeze-M Rocket Explosion (Russia)

The Breeze-M rocket was on a mission to deliver an ArabSat 4A satellite into GEO. Unfortunately, the Breeze-M experienced an engine malfunction early on that resulted in its placing the ArabSat 4A satellite into the wrong orbit. The malfunction caused the rocket to remain inactive for a time with a potentially dangerous amount of fuel on board. Less than one month later, the Breeze-M rocket fell back to earth and exploded in the atmosphere over Australia. The explosion caused additional debris, at least 1,000 fragments, to be distributed in LEO.

Space and International Commerce

Space-Faring Nations

Fifty years after their introduction, it is difficult to imagine a world without satellites. According to the Satellite Industry Association (SIA),[41] satellite industry revenue topped $106 billion dollars worldwide in 2006.

Noting “continued government and military demand and investment” and the “global appetite for more power, more mobility, more convergence,” SIA predicts a future market with even faster growth.[42] As Charles Cynamon[43] points out:

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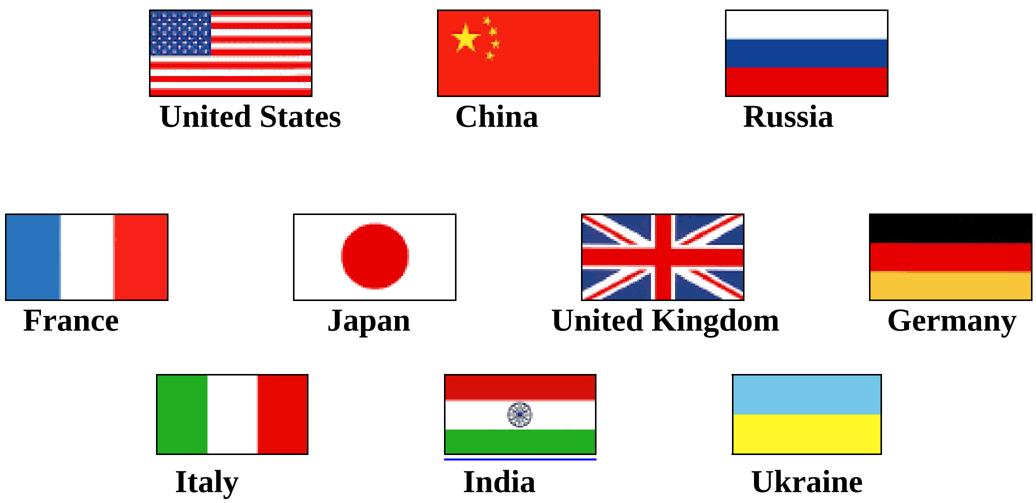
[41] Futron Corporation. State of the Satellite Industry Report. June 2006. Satellite Industry Association.<http://www.futron.com/pdf/resource_center/reports/SIA_2005_Indicators.pdf.> Accessed Fall 2007.
[42] Ibid.
[43] Cynamon, Charles H. “Protecting Commercial Space Systems: A Critical National Security Issue.” Research Report. Air Command and Staff College, Air University. Maxwell AFB, Alabama, April 1999.

> We are living in a society with an insatiable appetite for technology….We are increasingly choosing to remotely transact business, to connect our computers to the Internet, to have an 18” satellite dish in lieu of cable TV, and to have the ability to contact anyone from anywhere with as small a phone as possible….the average person hardly realizes the extent they rely on commercial space systems.[44]

Currently, the following countries are major “actors” in space.



Frank Klotz echoed a similar theme in a Council on Foreign Relations report: “While the public continues to identify space most closely with scientific exploration and high adventure, space has also become a big business and represents a huge investment in terms of capital assets and jobs.”[45] Might satellite technology be history’s answer to Gutenberg’s printing press? Never before has information – and commerce – traveled so quickly. Given the integrated state of today’s global economy, any major fluctuation in satellite capabilities has the potential to reverberate throughout multiple nations.

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[44] Ibid.
[45] Klotz, Frank G. "Space, Commerce, and National Security." Jan. 1999. Council on Foreign Relations.

Common Values

Space industry profits will exceed $250 billion by the year 2010, according to forecasts published by the BBC.[46] Technologies such as telecommunications, global positioning systems, broadband, and remote sensing are being further developed for use in space. Of utmost priority, however, is the need for heightened space situational awareness and space debris elimination measures. Without space debris elimination measures, the possibility of a crescendo, known as the "Kessler Effect," occurring at current debris levels remains high. In this scenario, large and small debris continually collide and fragment until the atmosphere at LEO becomes unusable. Space-faring nations would lose the ability for space exploration and technology such as The International Space Station (ISS) and Hubble Space Telescope might be compromised. In fact, the NASA space shuttle could also be rendered inoperable.

In July 2007, the United Nations voted to adopt orbital debris mitigation guidelines. Many space-faring countries were already operating under similar guidelines established by the Inter-Agency Space Debris Coordination Committee (IADC) in 2002. However, the IADC argued that U.N. adoption of orbital debris mitigation guidelines was necessary. There has been little in the form of policy related to the use of space in regards to debris. The definitive policy to date has been the Outer Space Treaty *of 1967*. Article I of the treaty reads as follows:[47]

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[46] Shiels, Maggie. "Money-men see space for profit." 12 June 2002. BBC News, Science/Nature. <http://news.bbc.co.uk/1/hi/sci/tech/2038059.stm>. Accessed Dec. 28 2007.
[47] "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies." 1967. United States Department of State, Bureau of Verification, Compliance and Implementation. <http://www.state.gov/t/ac/trt/5181.htm>. Accessed Fall 2007.

> The exploration and use of outer space, including the moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind.

Market Limitations

Despite the claim that orbital slots will one day be owned, traded and sold in an efficient market,[48] the foreseeable future remains one of universal access. The 2006 space policy of the United States "rejects any claims to sovereignty by any nation over outer space or celestial bodies…and rejects any limitations on the fundamental right of the United States to operate in and acquire data from space."[49] This precept echoes the declarations of the United Nations nearly four decades ago: "Outer space, including the moon and other celestial bodies, shall be free for exploration and use by all States without discrimination of any kind, on a basis of equality and in accordance with international law."[50]

This "Global Common"[51] of outer space offers vast opportunities for a host of government and commercial applications, while featuring a unique legal aspect, the lack

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[48] Scheraga, Joel D. "Establishing Property Rights in Outer Space." Cato Journal 6:3 (Winter 1987). 889-895.

[49] United States National Space Policy. 31 Aug. 2006. United States Office of Science and Technology Policy, Executive Office of the President. <http://www.ostp.gov/html/US%20National%20Space%20Policy.pdf> Accessed Fall 2007.

[50] "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies." 1967. United States Department of State, Bureau of Verification, Compliance and Implementation. <http://www.state.gov/t/ac/trt/5181.htm>. Accessed Fall 2007.

[51] Hörl, Kay-Uwe. "Legal and Technical Considerations of Space Debris." Institute of Air and Space Law, McGill University, Montreal, Quebec, 2000.

of property rights. According to research on an establishment of such rights, this missing legal provision affects the orbital environment directly:

> By assigning property rights, a market is established in which the rights to orbital slots may be bought and sold. Selfish maximization of the profit from property rights will lead to a socially efficient outcome. The negative externalities will be eliminated.[52]

Even assuming the assignment of property rights that enable free markets to function efficiently,[53] a commercialized, profit-based market for space debris elimination requires a level of active demand for mitigation that has yet to emerge. Given the current debris population, market forces have little influence over prevention or remediation outside of insurance and space policy domains. Technologies for removal are untested and launch capabilities limited and expensive.

Also absent from space law is a salvage taxonomy. While orbits are free from ownership, every piece of debris from millimeter-sized paint flakes to frozen chunks of fuel remains the property of its original state or commercial owner.[54] According to space lawyer Arthur M. Dula, this factor adds to the complexity of debris removal as problems might result if one country eliminated another country's debris, even inadvertently.[55]

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[52] Scheraga, Joel D. "Establishing Property Rights in Outer Space." Cato Journal 6:3 (Winter 1987). 889-895.
[53] Bickers, K.N. and John T. Williams. Public Policy Analysis: A Political Economy Approach. New York: Houghton Mifflin Company, 2001.
[54] Dula, Arthur M. Space law expert. Personal Interview. Houston, Texas. 07 Nov. 2007.
[55] Dula, Arthur M. Space law expert. Personal Interview. Houston, Texas. 07 Nov. 2007.

The current space policies of the United States and other space-faring nations do not portend movement towards a space property auction market in the foreseeable future. Therefore, decision-making will continue to be based on policy guidance, rather than economics. In this light, how can existing policies be improved to move debris elimination processes forward? What new policy tools might bring the problem of debris remediation to the global government agenda?

International Political Overview

Prior to an analysis of space debris regulations, a note on limitations is necessary. First, space is a relatively new policy arena. Though the issue of space debris has been acknowledged for decades, much remains unknown about the long-term prospects of space for human use. Second, debris governance has evolved slowly, partly due to the growing stakeholder base in space exploration. The two-way race between the United States and the former Soviet Union in the 1950s and 1960s is today represented by the partnership in the International Space Station, which includes the U.S., Russia, Canada, Japan, Brazil, and the members of the European Space Agency. Additionally, as of August 2007,[56] 48 countries hold satellites in orbit and 67 countries belong to the United Nations Committee on the Peaceful Uses of Outer Space.[57]

[56] Gallagher, Nancy and John Steinbruner. "Reconsidering the Rules for Space Security." Working paper, Center for International and Security Studies at Maryland. 2007. University of Maryland.
[57] United Nations Office for Outer Space Affairs. Committee on the Peaceful Uses of Outer Space: "Member States." 2006. <http://www.unoosa.org/oosa/COPUOS/copuos.html.>. Accessed Fall 2007.

Existing Space Law in Brief

The 1967 "Outer Space Treaty," as the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies is known informally, was partially modeled after the Antarctic Treaty of 1961.[58] The Antarctic document "sought to prevent 'a new form of colonial competition' and the possible damage that self-seeking exploitation might cause"[59] and similar language is seen in the space document drafted six years later. As Articles I and II state:

> The exploration and use of outer space, including the moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development…Outer space, including the moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty.[60]

The four agreements that followed the 1967 treaty expanded into areas of astronaut rescue, the registration of launched objects, and liability for damage caused by launched objects.[61] Article VII of the 1967 treaty put in place a framework for international liability and the 1972 Convention on International Liability for Damage Caused by Space Objects elaborated further, setting out guidelines for a claims

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[58] "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies." 1967. United States Department of State, Bureau of Verification, Compliance and Implementation. <http://www.state.gov/t/ac/trt/5181.htm>. Accessed Fall 2007.
[59] Ibid.
[60] Ibid.
[61] United Nations Treaties and Principles on Space Law. Home page. 2006. <http://www.unoosa.org/oosa/en/SpaceLaw/treaties.html>. Accessed Dec. 2007

committee and monetary reimbursement for damages.[62] It also called for any damage reward to be directly reported to the Secretary-General of the United Nations and be made public.[63]

While there is no treaty that specifically addresses orbital debris, the Inter-Agency Space Debris Coordination Committee (IADC), an independent and international scientific consortium, seeks to promote the exchange of information and to encourage the remediation of existing space debris.[64] Members include India, Russia, China, Japan, the Ukraine, the European Space Agencies, Spain, Britain, Italy and the United States.[65] Research team discussions with domestic experts revealed awareness of the need for global cooperation in this area, though not necessarily in a codified fashion. A new treaty addressing the space debris environment or a debris addendum to the 1967 Outer Space Treaty were both openly rejected.[66]

International Space Policy Organizations

There are several space policy organizations. The four most prominent are as follow.

The United Nations Office of Outer Space Affairs

The United Nations Office of Outer Space Affairs (UNOOSA) was born in the early days of space exploration. The original concept for The Committee on the Peaceful

[62] "Convention on International Liability for Damage Caused by Space Objects." 1972. United Nations Office for Outer Space Affairs.<http://www.unoosa.org/oosa/en/SpaceLaw/liability.html> Accessed Fall 2007.
[63] Ibid, Article XIX.
[64] Inter-Agency Space Debris Coordiation Committee. "Purpose." 4 Oct. 2006. <http://www.iadc-online.org/index.cgi?item=torp>. Accessed Fall 2007.
[65] Inter-Agency Space Debris Coordination Committee, "Membership."
[66] United States. U.S. Domestic agency official. In-person interview with Stephanie M. Cook and Stephanie D. Silva. Oct. 2007.

Uses of Outer Space (COPUOS) was a U.N. effort to put together an ad hoc body to facilitate international cooperation in the peaceful uses and exploration of outer space. The Committee began with 24 members. Now at 67 members, it is one of the largest committees in the United Nations.[67] Governmental and non-governmental organizations (NGO) provide and exchange information on space activity with COPUOS, enabling UNOOSA to provide guidelines and information in areas such as the registry of space vehicles and launchings. In order to begin to address the problem of orbital debris, the UN-arm of COPUOS recognized officially the problem of orbital debris and the need for debris mitigation guidelines.

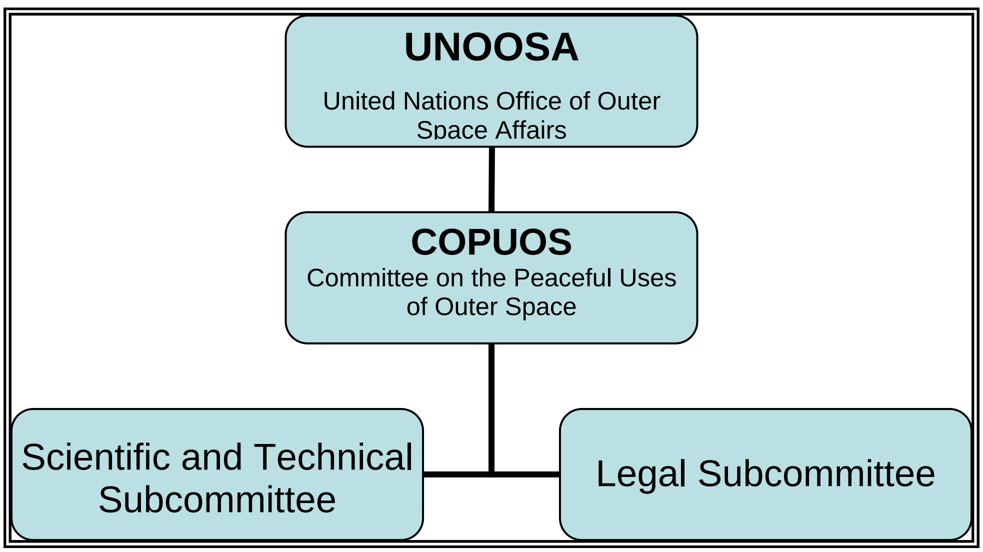

Figure 2: United Nations Office of Outer Space Affairs Organization Chart

[67] United Nations Office for Outer Space Affairs: History and Overview of Activities. 2006. <http://www.unoosa.org/oosa/en/COPUOS/cop_overview.html> Accessed on: November 18, 2007

IADC

The IADC is an international forum of governmental bodies, primarily academics and scientists, studying man-made and natural orbital debris. According to the IADC website, the purpose of the organization is:

- To exchange information regarding space debris research activities among member space agencies
- To review progress of ongoing cooperative activities
- To facilitate opportunities for cooperation in space debris research
- To identify debris mitigation options[68]

The IADC has been successful in its efforts to bring orbital debris mitigation guidelines to the international community. In 2001, the IADC introduced space debris mitigation guidelines based in part on prior work done by the International Academy of Aeronautics and various space agencies. In June 2007, UN-COPUOS approved space debris mitigation guidelines based on revised IADC Space Debris Mitigation Guidelines.

There are 11 national governments and space programs participating in the IADC that assist in providing international perspectives on alleviating the problem of orbital debris.

[68] Inter-Agency Space Debris Coordination Committee presentation to the 34th Session of the Scientific and Technical Subcommittee of the United National Committee on the Peaceful Uses of Outer Space. 1997. <http://www.iadc-online.org/index.cgi?item=docs_pub.> Accessed Fall 2007.

IADC-Committee Member Organizations

IADC-Committee Member Space Agencies

The IADC mitigation guidelines are based on four general principles.[69]

- Limit debris during normal operations
- Minimize the potential for on-orbit breakups
- Disposal of post-mission satellites and satellite launchers
- Prevention of on-orbit collisions

Orbital Debris Mitigation Policy Milestones

December 2000	The U.S. Government implements *Orbital Debris Mitigation Standard Practices* nationally
October 2002	The Inter-Agency Debris Committee (IADC) establishes orbital debris mitigation guidelines.
June 2007	The United Nations Committee for the Peaceful Uses of Outer Space approves orbital debris mitigation guidelines, a standard now applicable to all U.N. member nations.[70]

[69] Inter-Agency Space Debris Coordination Committee, Space Debris Mitigation Guidelines. 15 Oct. 2002. <http://www.iadc-online.org/docs_pub/IADC-101502.Mit.Guidelines.pdf.> Accessed Fall 2007.
[70] Differentiating between an “agreement” and “non-binding resolution.” The latter has moral force but no legal force.

International Academy of Astronautics

The International Academy of Astronautics (IAA) is a nongovernmental, non-profit institution of leading experts with over 1700 members from over 77 countries. The IAA focus is on the scientific, rather than political, goals of space exploration and three main goals:[71]

- To foster the development of astronautics for peaceful purposes
- To recognize individuals who have distinguished themselves in a branch of science or technology related to astronautics
- To provide a program through which the membership can contribute to international endeavors and cooperation in the advancement of aerospace science, in cooperation with national science or engineering academies

The United Nations recognized the IAA in 1996. The IAA encourages international scientific cooperation through the work of scientific committees. Each committee seeks to publish a position paper on specific research topics. Recent IAA papers have touched on space debris, microsatellites, international cooperative endeavors, lunar and Martian exploration, and space tourism. The IAA also has working groups tasked with non-space related topics such as: "easing East-West tensions," "the progressive integration of European economies," "the emergence of the Asian economic

[71] "About Us." International Academy of Astronautics. (n.d). <http://iaaweb.org/content/view/246/378/>. Accessed Nov. 23 2007.

revolution," and "cost, scope, complexity and other pragmatic considerations associated with space exploration dictate cooperation among nations."[72]

International Telecommunications Union

The International Telecommunications Union (ITU) is a body of the United Nations responsible for allocation of the worldwide radio spectrum and is the U.N. counterpart to the Federal Communications Commission (FCC) in the U.S. In the United States, regulatory responsibility for the radio spectrum is divided between the Federal Communications Commission and the National Telecommunications and Information Administration. The FCC is an independent regulatory agency that administers spectrum for non-Federal use and the NTIA (an operating unit of the Department of Commerce) administers spectrum for Federal use. Within the FCC, the Office of Engineering and Technology provides advice on technical and policy issues pertaining to spectrum allocation and use.[73]

The ITU controls international orbital slots, based on a first-come, first-serve basis. The focus of the ITU is as facilitator of communication ability. The ITU mission has three main focus areas:

- Radio communication
- Standardization
- Development

[72] "Space Expectations: A Cosmic Study by the International Academy of Astronautics." (n.d). <http://www.space-expectations.org/about.php.> Accessed Dec. 2007.
[73] Federal Communications Commission Radio Spectrum Home Page, Office of Engineering and Technology. 19 Nov. 2007. <http://www.fcc.gov/oet/spectrum/>. Accessed Fall 2007.

International Space Law

The United Nations Office on Outer Space Affairs provided administrative support for the United Nations Conferences on the Exploration and Peaceful Uses of Outer Space (UNISPACE) conferences in 1968, 1982, and 1989.[74] The three conferences were integral to the body of existing space law. The five major treaties governing international relations in outer space are as follows:

- *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space or the Outer Space Treaty of 1967*
- *The Convention on International Liability for Damage Caused by Space Objects of 1973*
- *The Registration Convention of 1976*
- *Agreement on the Rescue of Astronauts*
- *The Moon Agreement of 1979*

Fully 98 governments are party to the 1967 Outer Space Treaty (OST), including all of the major space-faring nations. In contrast, only 13 nations have ratified the Moon Agreement. The Outer Space Treaty sets forth the principle that there is no "ownership" of outer space resources. The spirit of the Outer Space Treaty is an idealistic view of "the peaceful exploration" of outer space and the common right of mankind to explore outer space. The Registration Convention addressed administrative aspects such as the registration of a space vehicle with the UN and the Liability Convention and defined a liable party as, in effect, the "launching country." Further, according to Niklas Hedman, Chief of Committee Services and

[74] "United Nations Office for Outer Space Affairs." <http://www.unoosa.org/oosa/index.html> Accessed on: 27 December 2007

Research at UNOOSA (The United Nations Office for Outer Space Affairs), national governments are not forbidden from placing installations and/or stations on outer space resources such as the moon.

The Registration Convention and Convention on International Liability

The Registration Convention and Convention on International Liability for Damage caused by Space Objects are facilitated by the United Nations and national agencies, respectively. The Registration Convention requires that state-owners register space technology with the United Nations. The United Nations Office of Outer Space Affairs (UNOOSA) manages the official registration database. The United States maintains registration information through domestic space administration agencies such as the FAA and FCC, while European space entities are likely to maintain registration of space technology with the International Telecommunications Union (ITU).

International Conflict Resolution

The International Court of Justice (ICJ) is the official judicial arm of the United Nations. The Court hears legal disputes upon the request of a member state or member states in accordance with international law with an advisory opinion to follow. The ICJ also assists in answering legal questions referred to it by authorized United Nations organs and other specialized agencies.[75] The benefit of utilizing the official arm of the United Nations to resolve international outer space issues is clear when one considers the historic role played by the U.N. in establishing outer space principles such as those set forth in 1967 Outer Space Treaty.

[75] ICJ <http://www.icj-cij.org/court/index.php?p1=1> Accessed on November 18, 2007

Some argue that maritime law should inform international state conflicts in outer space. In fact, the ICJ is the international judicial body that upon request hears maritime disputes and renders an advisory opinion. Some examples of disputes recently under the jurisdiction of the ICJ are as follows:

- Dispute regarding Navigational and Related Rights (Costa Rica v. Nicaragua).[76]
- Case Concerning Maritime Delimitation in the Black Sea (Romania v. Ukraine).[77]
- Sovereignty over Pedra Branca/Pulau Batu Puteh, Middle Rocks and South Ledge (Malaysia/Singapore).[78]

The ICJ does not take a "request for hearing" from individuals. The Court is dedicated to U.N. member nations with the caveat that once judgment is delivered, it is binding. According to Article 94 of the United Nations Charter, "Each Member of the United Nations undertakes to comply with the decision of [the Court] in any case to which it is a party"[79].

The drawback to an ICJ hearing is that a case can take anywhere from two to ten years (or more) from the year the case was originally filed up to final judgment. The issue of timeliness is significant when one considers that commercial applications of space-based technology are time sensitive due to emerging technologies. To date, the ICJ has

[76] Dispute regarding Navigational and Related Rights (Costa Rica v. Nicaragua). No. 133. International Court of Justice. <http://www.icj-cij.org/court/index.php?p1=1>. Accessed Nov. 18 2007.
[77] Case Concerning Maritime Delimitation in the Black Sea (Romania v. Ukraine). No. 132. International Court of Justice. <http://www.icj-cij.org/court/index.php?p1=1>. Accessed Nov. 18 2007.
[78] Sovereignty over Pedra Branca/Pulau Batu Puteh, Middle Rocks and South Ledge (Malaysia/Singapore). No. 130. International Court of Justice. 2003.
[79] "International Court of Justice: Chapter XIV." International Court of Justice website. <http://www.unoosa.org/oosa/en/SpaceLaw/liability>. Accessed Fall 2007.

not been asked to hear a space law conflict. Some argue that the ICJ is not a realistic option for space dispute resolution because it lacks the ability to enforce a judgment.

International Policy Recommendations

Existing Treaty Options: Outer Space Treaty of 1967

The International Convention on Liability for Damage Caused by Space Objects has not been invoked with any significance to date despite a number of debris-causing events within the last ten years or so. One reason for this may be due to the absence of an enforcement body specific to outer space law. The International Court of Justice (ICJ), the judicial branch of the U.N., hears territorial and maritime disputes at the request of member states. As a U.N. judicial body, the ICJ is likely to one day review a space liability dispute. In the absence of strict enforcement and in the event of a major space debris incident, space-faring nations are likely to rely on collective pressure or bilateral negotiations to recover damages from the launching country.

The Outer Space Treaty of 1967, the Convention on International Liability for Damage Caused by Space Objects of 1973, the Registration Convention of 1976, the Agreement on the Rescue of Astronauts, and the Moon Agreement of 1979 are inconsistent in the use of terminology. Clarification of terminology will diminish the likelihood that countries new to space exploration will misinterpret Outer Space Treaty principles, guidelines, and norms, including those found within space debris mitigation guidelines.

Clarify Space Terminology

Space terminology varies within the five space agreements. The most recent outer space treaty is nearly three decades old, and levels of exploration and international cooperation have changed drastically within this timeframe. In order to ensure global understanding of the treaty frameworks, language must be consistent, and clarifying dated definitions would be one step toward this goal.

Establish a Registration Timeframe

The Registration Convention of 1976 does not require that a country register its space technology within a specific timeframe. There are inherent problems with this. For example:

- The U.N. registration database at any given time does not include an accurate accounting of space technology (e.g., satellites, space vehicles) currently in outer space.
- Countries with emerging technologies and/or countries that were once priced out of space technologies can now afford to launch a satellite.
- The possibility of a conjunction between an unregistered space satellite (the existence of which was previously unknown) and a registered space satellite or other technology.

An established registration timeframe should address some of these issues.

Establish "Transfer-of-ownership" Guidelines

The Registration Convention of 1976 does not provide guidelines specific to transfer-of-ownership in the event of bankruptcy, sale, or other qualifying event. The

Iridium Satellite Constellation, a relay system for voice and data phones, fell into Chapter 11 bankruptcy in August of 1999. In the absence of a contingency plan to transfer ownership of the constellation, Iridium satellites were (presume that there was more than one) scheduled to be sent out of orbit to be destroyed in Earth's atmosphere.[80]

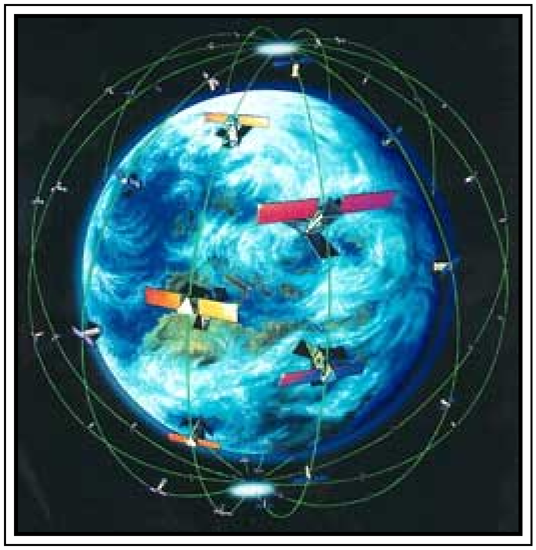

Figure 3: Iridium Constellation

Before the bankruptcy was final, a private group of investors purchased Iridium. As technology advances, global dependency on space-based technologies will also increase as will the probability of bankruptcy, sale, or other qualifying events. Transfer-of-ownership guidelines would address some of these problems.

International Policy Considerations

There are two schools of thought with regard to a new treaty specific to space law and space resources. International relations (IR) "realists" believe that superpowers such as the United States must maintain viable space operations options. IR "idealists" argue

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[80] Ray, Justin. "Pioneering Iridium Satellite System Reaches Dead End." Spaceflight Now 18 Mar. 2000. <http://www.spaceflightnow.com/news/0003/18iridium/>. Accessed Oct. 2007.

that there is a need for international treaties to prohibit weapons or dual-use technology in the space environment. IR idealists further argue that the “weaponization” of space threatens to become a “race” in the manner of the Cold War. In general, there is no policy panacea. Rather, a combination of one or more of the following recommendations will facilitate space debris removal.

- **Voluntary Non-binding Agreements (international agreements)**
- **International Research Consortia (research and technology initiatives)**
- **Rules-of-the-Road Guides to Mitigation (operational definitions)**

The “Voluntary Non-binding Agreement” Option

NASA legal counsel Steven A. Mirmina wrote a journal article for *The American Journal of International Law* titled “Reducing the Proliferation of Orbital Debris: Alternatives to a Legally Binding Instrument.”[81] In the article, Mirmina asserts that voluntary agreements are effective and serve as an important alternative to legally binding agreements. Mirmina describes how various countries came together to address the growing concern over the continued proliferation of weapons of mass destruction.

Partner members of the Missile Technology Control Regime (MTCR) Agreement, an agreement dedicated to the prevention of continuing proliferation of weapons of mass destruction, initiated guidelines[82]to be followed voluntarily by MTCR partner countries. The agreement is a living document in that it is open to revision as technology advances.

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[81] Mirmina, Steven A. “Reducing the Proliferation of Orbital Debris: Alternatives to a Legally Binding Instrument.” The American Journal of International Law 99:3 (2005): 649-662.
[82] “Missile Technology Control Regime (MTCR) Equipment and Technology Annex. Federation of American Scientists. <http://www.fas.org/nuke/control/mtcr/text/mtcr_handbook_guide-annex.pdf>. Accessed Oct. 15 2007.

The Wassenaar Agreement is an export controls agreement for conventional arms and dual use technologies. Some 40 member countries adhere to the agreement despite maintaining individual export controls. One of the reasons a voluntary agreement would work has to do with national sovereignty. If, as with the Wassenaar Agreement, individual nations are left to regulate themselves and yet remain responsible to a collective reporting mechanism that fosters transparency, the nation state is more likely to participate. There are other means by which to hold a state responsible for damages caused by errant satellites at the end of its orbital life. The Liability Convention entered into as of September 1972 under U.N. auspices holds the "launching state" of a satellite responsible for damages caused by the satellite.

International Research Consortia

There are currently several international working groups involved in orbital debris mitigation and elimination efforts. However, it is not clear if there is any level of real coordination and information sharing among these. There is a common sense need for some level of communication among them in order to alleviate the potential for duplication and for effective and efficient progress on the problem of orbital debris. The IADC continues to work to facilitate the exchange of information specific to orbital debris and research is also being carried out by the European Space Agency (ESA), the International Academy of Astronautics (IAA), and others on the problem of orbital debris.

Dr. Michael Valley of Sandia Laboratories is involved in a multinational effort to address some of the problems associated with orbital debris mitigation and elimination such as space situational awareness (debris detection and tracking), surveillance systems,

observational technology and removal technology. Dr. Michael Valley, Dr. Victor Shargorodsky (Institute of Precision Instrument Engineering in Moscow and Designer General of Laser/Optical Systems for the Russian Aerospace Industry), Dr. Alexander Sergeev (Deputy Director of the Russian Academy of Sciences Institute of Applied Physics (IAP) in Nizhny Novgorod, Russia), and Chinese experts in the field round out the work group. This international effort is also investigating emerging technologies for orbital debris elimination. A report on their findings is scheduled to be published in February 2008. Topics include the following:[83]

- Characteristics of space debris distributions for geostationary, circular, high and low orbits, including manned space flight orbit
- Methods for detection, measurement of angular coordinates, and integral photometry for low-orbit space debris
- Surveillance systems for low and high orbit space debris with maximum optical information
- Space debris targeting challenges
- Application of highly sensitive nonlinear optical methods for imaging space debris
- Evaluating the possibility of control of the space debris motion vector using phase conjugation

International Organization for Normalization

According to Dr. Emma A. Taylor, a member of the International Organization for Normalization (ISO), the ISO currently has two committees that are technical and

[83] Valley, Michael. "Research-Orbital Debris." Email to: Stephanie M. Cook 23 November 2007

operational in nature working to standardize orbital debris mitigation processes. Dr. Taylor is a working group member of both the U.K. delegation to ISO/TC 20, Aircraft and space vehicles, and SC 14, Space systems and operations. She has written of the need for an internationally agreed set of standards, technical specifications and technical reports in order to provide “a common global framework for interpretation and implementation of these debris mitigation measures.”[84]

“By defining the scope of these standards to be consistent with existing agreed measures, it is anticipated that both ISO members and space sector industry members will use these standards. Each of these standards will represent internationally agreed practices for a particular aspect of debris mitigation (e.g., disposal from the geostationary orbit).”[85]

A Common Sense “Rules of the Road” Guide

A comprehensive guide to the “rules of the road” guide for space operations appears to be a practical way to standardize mitigation process and procedures. Space agencies (e.g., NASA, ESA), space research consortia (e.g., IADC, IAA), national agencies and commercial interests must commit to standard mitigation efforts and information sharing. Orbital debris mitigation practices must become standard operating procedure in areas of space technology production. Currently, industry players such as Boeing, Lockheed, and Northrop Grumman offer mitigation as an option for satellite buyers.

Rather than simply offering space hardware buyers “optional” debris mitigation technology, the standardization of such measures by industry leaders would move the

[84] Taylor, Emma A. “Reducing Orbiting Space Debris.” *ISO Focus(Oct. 2005):14*
[85] Ibid.

debris issue forward in a proactive manner. Two considerations are that industry cannot assume risk for the global common of outer space and that the cost of debris elimination technologies later will far exceed the cost of mitigation measures implemented now.

Creating a Market for Space Debris Elimination

Today there are thousands of markets that cater to a variety of subjects and demographics but all markets have one thing in common in that they connect co-dependent organizations and individuals. This interdependence is the lifeline of the market. This interdependence is typically in the form of consumer/producer or demander/supplier relationships. The two ideas presented in this section, X-PRIZE and Seeding a Business Cycle, use the market concept for the elimination of space debris.

X-PRIZE

The X-PRIZE is a world-wide cash prize that rewards technological innovations. In the automotive, space, and many other fields the X-PRIZE touches a wide range of technologies. In the words of X-PRIZE founder and CEO, Peter Diamandis, “the prize galvanizes huge amounts of global interest.”[86] Creating global interest and spreading an entrepreneurial mentality have the potential to spark the formation of a competitive market that can create inexpensive and innovative solutions. This “model” might provide an avenue for renewed interest and/or innovation.

Public “prize” model topics come from many different sources. If an industry is “stuck” due to high technology costs or the lack of technology or if someone wants to see

[86] Diamandis, Peter “X PRIZE Foundation Featured on PBS Series “WIRED Science” WIRED Science. 2007 X PRIZE FOUNDATION 27 Dec 2007 <http://www.xprize.org/>

if a particular task can be completed, this “prize” approach may be the right way to stimulate directed efforts.

From launching costs to space assets, there is nothing inexpensive about space technology. As a solution to funding the technology development needed to eliminate space debris, the global interest generation concept demonstrated by a “prize” model might be effective. Global interest has the potential to not only spark inexpensive and innovative elimination technologies but are also an opportunity to create global awareness. Awareness could lead to improved prevention techniques and help reduce future debris numbers.

Seeding a Business Relationship

All business cycles originate from interdependent relationships between economic actors. For example, insurance companies are dependent on clients owning automobiles, homes and many other items. Auto manufactures are dependent on consumer transportation needs and geographical locations. Consumers create the need for automobiles and automobiles create the need for insurance. Therefore, insurance companies are dependent on auto manufacturers and this dependence forms a business relationship.

Another example of a business relationship is one that involves the use of space. A form of satellite television known as DIRECTV utilizes a satellite constellation in GEO to transmit to the earth-based client. Satellite manufacturers like Boeing build the DIRECTV satellites. In one case Boeing acts as the company and DIRECTV acts as the client. In the other, DIRECTV is the providing company and the general public is the client.

Seeding a business relationship creates the opportunity for a supplier/consumer or company/client nexus to grow and provides one example of how the market concept can be used to eliminate space debris via insurance. Insurance companies base their fees on many different variables. One of those variables is an assessment of client risk of loss. Ideally, such an assessment is based on objective data such as actuarial tables. A space debris elimination market could allow for a customer like DIRECTV to purchase satellite insurance. This insurance premium would reflect a risk assessment provided by an insurance company not unlike the accident risk assessment of an auto insurance company. In this case, it would reflect such factors as the operational orbit chosen and the debris numbers in that orbit.

In order for the debris elimination business example to be feasible, insurance is a requirement. Current debris populations have not yet reached critical levels so the risks are not particularly significant. If space debris numbers continue to increase, so will risk probabilities and the need for a solution will be emerge over time. In conclusion, to help offset the costs of employing debris elimination technologies, the business cycle solution could be employed.

Domestic Policy Recommendations

United States space policies have evolved to a formal recognition of the debris problem through the creation of national space debris mitigation guidelines. Although decades of research have given policymakers multiple options for debris remediation, the research remains untested. A debris removal demonstration is needed and should be domestically proposed and international in scope. Signaling the serious nature of the problem through global outreach, such a demonstration would enable the scientific

community to move beyond theoretical debris removal techniques to practical applications. A conduit for funding of applied research would then be opened, with an exercise of actual debris removal as the next logical step towards enhanced science and policy.

Funding goes hand-in-hand with a demonstration. A successful demonstration of debris removal would offer an international platform for funding aimed at the long-term goal of a sustainable space environment. Existing debris is a sunk cost; focusing on future remediation would enable consideration of a global funding construct. For example, a small fee could be incorporated into each satellite launch to build a funding pool that would be made available once international consensus was reached on viable technologies. With nearly 50 countries investing in space assets today, long-term prospects speak to the logic of pooled resources for future remediation efforts.

Domestic Outreach

International communication was a key component of this project's aims as the "borders" of outer space cover the entire globe. Input was actively sought from Canadian, British and Australian USSTRATCOM liaisons, both directly and at the *Strategic Space and Defense Conference* held in October 2007 in Omaha.[87]

The research team next initiated contact with China, Russia, Ukraine, Italy, France, Germany, India, Japan and the European Space Agency after submitting a panel of questions for review and approval by the USSTRATCOM Judge Advocate General's

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[87] Strategic Space and Defense Conference. October 9-11, 2007, Omaha, Nebraska. http://www.stratspace.org/archive

office. Outreach directed at the IADC representatives from the above listed countries took place from October 29 to November 1, 2007; United States IADC representative Dr. Nicholas Johnson was copied on all correspondence. To date, France, Germany and the United Kingdom have responded.

France stated that as of October 29, a specific piece of space legislation was being readied for publication by the French Parliament which would require French industry compliance with debris mitigation rules. Additionally, work is underway to organize workshops and conferences within France's aerospace industry to promote space debris issues. In regards to possible participation in a global "clean up fund," France responded affirmatively, stating that a "good awareness" of the problem exists in that country."[88]

Noting that satellite industry infrastructure is an important part of their domestic economy, Germany expressed concern regarding the debris problem. Should development of a "feasible, reasonable and sustainable" solution for space debris present itself, the German Space Agency is "prepared to take an active, responsible-minded role in the international stakeholder community."[89]

The United Kingdom advised that while there have been previous proposals for a levy or fund to help keep space "open for business," such a concept is currently difficult to consider without further details about participation and implementation. "Commercial interests are already leading to operators removing satellites from the GEO ring at the end of their useful life. This is clearly a good model, with most understanding the need to go

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[88] Inter-Agency Space Debris Coordiation Committee, Correspondence from French Representative. E-mail to Stephanie D. Silva. 05 Nov. 2007.
[89] Inter-Agency Space Debris Coordination Committee, Correspondence from German Representative. E-mail to Stephanie D. Silva. 13 Nov. 2007.

as far above the operational region as possible."[90] Ongoing international response to outreach efforts will be updated accordingly.

Domestic Policy: U.S. Orbital Debris Guidelines

Official U.S. space policy addresses space debris directly as follows:

> Orbital debris poses a risk to continued reliable use of space-based services and operations and to the safety of persons and property in space and on Earth. The United States shall seek to minimize the creation of orbital debris by government and non-government operations in space in order to preserve the space environment for future generations.[91]

Following NASA's lead in 1995, a joint effort between the space agency and the Department of Defense produced orbital debris mitigation standards for the United States in 1997.[92] Guidelines apply to all agencies in the United States government with authority over space activities, including launch and re-entry.[93] These entities include the Federal Aviation Administration (FAA), the Federal Communications Commission (FCC), and the National Oceanographic and Atmospheric Administration (NOAA).

The guidelines encompass four major objectives:[94]

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[90] Inter-Agency Space Debris Coordination Committee, Correspondence from United Kingdom Representative. E-mail to Stephanie D. Silva. 26 Nov. 2007.
[91] United States National Space Policy. 31 Aug. 2006. United States Office of Science and Technology Policy, Executive Office of the President. <http://www.ostp.gov/html/US%20National%20Space%20Policy.pdf> Accessed Fall 2007.
[92] "Orbital Debris Mitigation." NASA Orbital Debris Program Office, November 9, 2007.
[93] "Orbital Debris Mitigation: Regulatory Challenges and Market Opportunities." Futron Corporation, March 15, 2006.
[94] <u>U.S. Government Orbital Debris Mitigation Standard Practices</u>, NASA Orbital Debris Program Office.

- Control of debris released during normal operations
- Minimization of debris generation resulting from accidental explosions
- Selection of safe flight profile and operational configuration
- Post-mission disposal

Though a step in the right direction, these guidelines are not legally binding, therefore there is no level of accountability enforceable by statute.[95] Additionally, according to a Futron Corporation report, "National security and other government programs are generally granted orbital debris waivers today, demonstrating that the current regulatory regime is relatively lenient in these cases."[96]

U.S. Department of State

Though the FCC and FAA channel satellite license applications through the State Department, a State Department official indicated that such domestic procedures are generally "pro forma in nature," as foreign policy issues rarely come up in satellite licensing processes. When foreign policy and space usage collide, however, as with the Chinese anti-satellite test of January 2007, diplomatic representation does take place. Stating that the Chinese actions were "irresponsible and inconsistent"[97] with IADC and U.N, guidelines, a State Department official stated that this viewpoint was communicated directly to the Chinese government.[98]

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[95] Orbital Debris Mitigation: Regulatory Challenges and Market Opportunities," Futron, 2006.
[96] Orbital Debris Mitigation: Regulatory Challenges and Market Opportunities," Futron, 2006.
[97] United States. State Department official. Telephone interview. Nov. 2, 2007. Typically, such a government-to-government communication will take the form of a "demarche" delivered from an embassy to the equivalent of the Department of State in the other country.
[98] Ibid.

On a broader scale, the State Department[99] reports positive U.N. responses to proposals to level the international playing field in regards to formal acceptance of debris mitigation guidelines, noting that emplacement of worldwide standards is simply good practice."

Domestic Administration

National Aeronautics and Space Administration

At the forefront of the war on orbital debris is NASA. Chartered in 1958,[100] the agency has accomplished stunning feats from putting a man on the moon to helping construct the International Space Station. Dr. Nicholas L. Johnson, the United States IADC Representative, was a major source of information for this project and heads NASA's Orbital Debris Program Office at Johnson Space Center in Houston, Texas. Recognized globally for leadership in regards to orbital debris research, the office encompasses everything from modeling and measurement of space debris to protection and re-entry issues.[101] Johnson wrote about the complex differences between space debris research and other scientific ventures in 2002:

> Orbital debris is not like astronomy where an order of magnitude error in the answer is sometimes acceptable, nor is orbital debris like rocket science where accuracies of plus or minus 0.0001 may be commonplace. We need to understand better the bounds of our uncertainties….Perhaps most importantly; we need to

[99] Ibid.
[100] NASA History Division, <http://history.nasa.gov>
[101] NASA Orbital Debris Program Office. <http://orbitaldebris.jsc.nasa.gov/index.html>

augment our academic expertise with a more complete appreciation for *how space systems actually operate* [italics added for emphasis].[102]

In regards to space operations, while improvement of space situational awareness (SSA) is a major focus for debris tracking, it may not be needed for remediation purposes. Johnson stated that debris tracking itself is not necessarily a prerequisite for debris elimination, noting that the U.S. Space Catalog is "reasonably complete" at 10 centimeters (viewing debris 10 centimeters in diameter (?) and larger).[103] Conversations with Dr. Johnson also elicited a wealth of information about the current state of international governance.[104] "National governments do not yet see a need to put money into debris removal," he stated. "There is no commercial application yet…Who is going to pay for [it]? Where will the money come from?"[105] Calling U.N. adoption of IADC debris mitigation guidelines a "tremendous success," Johnson explained its sphere of influence. "The space community has to adhere…by means of simple peer pressure."[106]

Federal Aviation Administration

The Office of Space Commercialization is the only segment of the Federal Aviation Administration related to space, and its name parallels its function.[107] Fostering private sector space investment is its main focus. As authorized by the Commercial

[102] Johnson, Nicholas. "The World State of Orbital Debris Measurements and Modeling." Acta Astronautica, 54 (2004), 267-272.
[103] Johnson, Nicholas. Interview via conference call.18 Sep. 2007.
[104] Ibid.
[105] Ibid.
[106] Ibid.
[107] Office of Commercial Space Transportation. Federal Aviation Administration.12 Sept. 2007.<htttp://www.faa.gov/about/office_org/headquarters_offices/ast/about/>. Accessed Fall 2007.

Space Launch Act of 1984, the office regulates and licenses commercial launches from both U.S. territories and by U.S. nationals launching outside of the United States.[108]

The process for commercial launch and re-entry licensure include a payload review and safety evaluation. According to FAA sources, review is limited by jurisdiction. "[The] FAA does payload review, but we don't get into orbital life of payload…The FAA does not deal with satellite companies themselves…we do not tell the satellite company you must go into such-and-such graveyard orbit."[109] Legally mandated to oversee financial requirements prior to launch licensure, the FAA dictates insurance requirements, which are higher for the commercial sector.[110]

FAA guidelines[111] specifically prohibit unplanned contact between orbiter and payload after separation. At end-of-life (EOL), orbital batteries are to be placed in a permanent discharge state and venting of all remaining fuel is required to prevent an explosion. In December 1997, the FAA suspended the license of Orbital Sciences Corporation's launch vehicle *Pegasus* due to a lack of fourth stage venting.[112] [113] Fourth stage venting is designed to allow for the proper dispensation of excess fuel. The FAA noted that while formerly implicit debris policies were made explicit by the U.S. orbital debris guidelines, enforcement isn't written into the regulations. "We cannot just 'do' policy like NASA or the Air Force," sources explained.[114]

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[108] Ibid.
[109] Telephone conversation with FAA official, Licensing and Safety Division. October 2007.
[110] Ibid.
[111] United States Code of Federal Regulations, Title 14, Subchapter C, sections 415.39 and 417.29
[112] "FAA Stops Pegasus Launch" (n.a.). December 15, 1997. Space Views Update. http://seds.org/spaceviews/971215/top.html. Accessed Fall 2007.
[113] Telephone conversation with FAA official, Licensing and Safety Division. October 2007.
[114] Conversations with FAA sources.

Federal Communications Commission

The FCC is responsible for non-governmental satellite licensure; similar to the FAA, therefore, commercial satellite operators are required to address the U.S. domestic debris guidelines in their license application. This requirement was emplaced in the fall of 2004, but the Office of Management and Budget did not dictate final, formal rules until October 2005. Industry officials objected to the application of new standards to existing satellites already in orbit or in the "pipeline" for launch. A compromise led to a transition period, wherein IADC guidelines for existing launches remained, and the U.S. additions were grandfathered in for new satellites.[115] In other words, new standards were adopted to facilitate compliance for mitigating debris by incorporating these guidelines into the design of new satellites.

The shift has not been problematic administratively. An FCC official told the research team that administrators are "not shy" about saying, "We have a problem with your debris plan." Usually, the licensee will work with the FCC to address any concerns. While there is no off-site audit of licensed equipment, there have been no known situations to date where a licensee has intentionally disregarded the rules.[116]

While enforcement options for such violations range from civil forfeitures to criminal penalties, an FCC official indicated that the administrative power of the FCC is enough to deter noncompliance. If the application is not in order, the official said, "We just sit on it."[117]

[115] Telephone conversation with FCC official, November 16, 2007.
[116] Ibid.
[117] Ibid.

National Oceanographic and Atmospheric Administration (NOAA)

Part of the Department of Commerce, NOAA involvement with space debris is two-fold, both on the licensing and tracking ends. As the “principal unit for space commerce policy,”[118] the agency holds licensing authority for space-based remote sensing systems used for land use management and weather tracking.[119] Operating under the Land Remote Sensing Policy Act of 1992, satellite operators are required to dispose of satellites in a manner “satisfactory to the President.”[120] Minimum license requirements were revamped in 2000, and specify, “If the satellite disposal involves atmospheric re-entry, the applicant must provide an estimate of the total debris casualty area of the system components and structure likely to survive re-entry.”[121]

In the tracking arena, NOAA monitors geometric storms, which directly affect existing debris. Geometric storms heat the atmosphere, which increases atmospheric drag on LEO satellites and can displace debris. According to the Space Environment Center, “Centers that maintain catalogs of satellites and space debris will have to recalculate the new orbits of the satellites and ‘space junk’ in their catalogs after these (storms). The Space Station and the Space Shuttle will probably have to maneuver to avoid space debris that has been shifted into a collision path with the station.”[122] After the 2003 *Columbia* accident, NOAA’s unmanned wind profilers over Texas, Arizona, Louisiana and Mexico

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[118] United States. United States Department of Commerce: NOAA Office of Space Commercialization. Home page. <http://www.nesdis.noaa.gov/space/>. Accessed Oct. 2007.
[119] Licensing of Commercial Remote Sensing Satellite Systems. http://www.licensing.noaa.gov/
[120] Land Remote Sensing Policy Act of 1992, Section 202, subsection b4. <http://thomas.loc.gov/cgi-bin/query/F?c102:1:./temp/~c102EKfr1d:e25701:>
[121] “Orbital Debris Mitigation: Regulatory Challenges and Market Opportunities.” Futron Corporation, March 15, 2006.
[122] Heckman, Gary. “Solar Maximum.” 1999. U.S. Department of Commerce, National Oceanographic and Atmospheric Administration. Space Environment Topics, Space Environment Center, Boulder, CO. <http://www.swpc.noaa.gov/info/SolarMax.pdf>.
Accessed Fall 2007.

were used to follow debris after it fell from the sky (Appendix C).[123] “Because the unmanned profilers automatically acquire wind data continuously from near the ground up to 53,000 feet, the times, horizontal and vertical positions of the falling fragments of *Columbia* were captured in the data.”[124]

The Space Insurance Industry

Expensive, catastrophic loss coverage, offered through a small group of specialized underwriters, gives space insurance a unique niche within the property insurance industry.[125] Coverage availability has grown due to market demand and insurance is often the second largest expense for satellite operators.[126] Satellite insurance has existed since 1965[127] and its worldwide insured value is in excess of $540 billion (Appendix D).[128]

Due to the huge liabilities associated with space operations, risk sharing among multiple underwriters is common as space hardware and launch operations are generally too expensive and high-risk to be underwritten by one carrier.[129] According to an industry source,[130] current underwriting schemes operate in a standard framework:

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[123] National Oceanographic and Atmospheric Administration, Profiler Map. <http://profiler.noaa.gov/npn/images/shuttle/shuttlePath.png>
[124] “Profiler Data Supports NASA in Shuttle Columbia Investigation.” 30 Mar 2005. NOAA Profiler Network, National Weather Service. <http://profiler.noaa.gov/npn/shuttleColumbia.jsp?markers=no>. Accessed Fall 2007.
[125] “Commercial Space and Launch Insurance: Current Market and Future Outlook.” Federal Aviation Administration. Fourth Quarter 2002. Quarterly Launch Report. <http://www.faa.gov/about/office_org/headquarters_offices/ast/media/q42002.pdf.> Accessed Fall 2007. <http://www.faa.gov/about/office_org/headquarters_offices/ast/media/q42002.pdf.> Accessed Fall 2007.
[126] Consortium Delivers Satellite Revolution.” Market 2006: 2. Lloyd’s of London. <http://www.lloyds.com/market/Issue2-2006-en/article3.htm.> Accessed Fall 2007.
[127] Kunstadter, Christopher T.W. The Economics of Space Operations: Insurance Aspects. Preservation of Near-Earth Space for Future Generations, Ed. John Simpson, Cambridge University Press. 1994.
[128] “The Space Insurance Market.” Atrium Space Insurance Consortium. E-mail to Stephanie D. Silva, Fall 2007.
[129] Insurance industry source correspondence. E-mails to Stephanie D. Silva. Nov. 2007.
[130] Ibid.

> By far the largest element of risk assessment and rating of a satellite is to look at factors such as the heritage of the components that are being used on the satellite…have they been used on many satellites before or are they being used for the first time? What are the manufacturers' and operators' experience...what level of redundancy remains on the satellite and what design margins exist?[131]

Damage from space debris is today covered by many "all-risk"[132] policies,[133] though multiple sources acknowledge a lack of interest in this area. From *The Economics of Space Operations* in 1994: "The space insurance community does not currently view the risks posed by orbital debris as particularly significant to its own business."[134] In 1997, the *New York University Environmental Law Journal* intoned: "The insurance industry has not yet fully realized the severity of the risk from orbital debris….insurers cannot quantify the risk…since neither the operators nor the insurance community have experienced the outcomes of this risk."[135] Ten years later, this experience still holds true. "There has never been a major pay-out from debris damage, so it is not on (insurers') radar," stated NASA's Dr. Nicholas Johnson of NASA [136] and an established insurance market analyst outside of the United States concurred.[137] "Unfortunately," wrote

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[131] Ibid.
[132] Smith, Delbert D. "Symposium on the Environmental Law Aspects of Space Exploration and Development: The Technical, Legal and Business Risks of Orbital Debris." New York University Environmental Law Journal, 6:1 (1997).
[133] Insurance industry source correspondence. E-mails to Stephanie D. Silva. Nov. 2007.
[134] Kunstadter, Christopher T.W. The Economics of Space Operations: Insurance Aspects. Preservation of Near-Earth Space for Future Generations, Ed. John Simpson, Cambridge University Press. 1994.
[135] Smith, Delbert D. "Symposium on the Environmental Law Aspects of Space Exploration and Development: The Technical, Legal and Business Risks of Orbital Debris." New York University Environmental Law Journal, 6:1 (1997).
[136] Johnson, Nicholas. Space debris expert and United States IADC Representative. In-person interview, NASA Orbital Debris Office. 7 Nov. 2007. Houston, Texas.
[137] Insurance industry source correspondence. E-mails to Stephanie D. Silva. Nov. 2007.

Kunstadler, “it would take a catastrophic loss to prove to the insurance community that the threat is real.”[138]

Though not on the front burner, insurance companies are beginning to examine risk scenarios involving projected losses from space debris, as space activities and their associated debris are forecasted to grow. Michael Taylor also wrote, “Increased space debris will eventually affect the cost of insurance for space operations.”[139] This prediction is reflected in a projected assessment conducted by an international space insurance body in 2002[140] where “2008 onwards” risks outline specific concerns about a domino-like effect in areas with heavy satellite concentration:

> Should one of the satellites in the constellation break-up…a debris cloud will form….In this situation, the risk of a collision with other satellites in the same or other constellations is greatly increased. Some models of this evolution suggest that entire constellations may be destroyed as the debris cloud forms.[141]

A glance at past satellite losses suggest the magnitude of potential loss to space insurers should this constellation scenario occur. In 2001, an *Ariane 5G* upper stage failure led to the loss of both the Artemis and BSAT-2B satellites, with a combined $150

[138] Kunstadter, Christopher T.W. The Economics of Space Operations: Insurance Aspects. Preservation of Near-Earth Space for Future Generations, Ed. John Simpson, Cambridge University Press. 1994.
[139] Taylor, Michael W. “Trashing the Solar System One Planet at a Time: Earth’s Orbital Debris Problem.” Georgetown International Environmental Law Review, 20:1.
[140] Risk Assessment conducted by established international space insurer. (2002). E-mail to Stephanie D. Silva, Fall 2007.
[141] Ibid.

million in claims.[142] That same year, cost of the failure of the Arabsat solar array ran $173 million and the breakdown of the PanAmSat solar array carried a $253 million price tag.[143] Clearly, hypothetical destruction of a satellite constellation could run into the billions.

Delbert Smith suggests that several market approaches might be used to discourage debris creation, including debris damage exclusions and premium increases.[144] Cynamon posits the provision of tax incentives to insurance companies who encourage responsible satellite construction through underwriting procedures, "analogous to the savings automobile insurers provide for air bags or alarms."[145] Proposals for a global insurance liability pool are discussed throughout the literature, though it has been pointed out that such a vehicle would be punitive in nature.[146] The current research project took a different approach to the power of resource pooling: evaluating the viability of an international fund for the purposes of debris remediation, once applicable technologies are demonstrated and verified.

Policy Methodology and Analysis

Policy cannot be formulated in a vacuum, nor can it be implemented overnight. To assess the political viability of debris remediation policy tools, several methodologies were considered. The calculation of global political and social costs required intricate

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[142] "Commercial Space and Launch Insurance: Current Market and Future Outlook." Federal Aviation Administration. Fourth Quarter 2002. Quarterly Launch Report. <http://www.faa.gov/about/office_org/headquarters_offices/ast/media/q42002.pdf.> Accessed Fall 2007.
[143] Ibid.
[144] Smith, Delbert D. "Symposium on the Environmental Law Aspects of Space Exploration and Development: The Technical, Legal and Business Risks of Orbital Debris." New York University Environmental Law Journal, 6:1 (1997).
[145] Cynamon, 1999.
[146] Taylor, Michael W. "Trashing the Solar System One Planet at a Time: Earth's Orbital Debris Problem." Georgetown International Environmental Law Review, 20:1.

weighting and discount rates beyond the scope of this project. Consequently, a qualitative strategy was employed, drawn from both expert interviews and an exhaustive literature survey, resulting in a policy recommendation that marries a rational platform with an incremental approach.[147] (See Appendix E).

A final constraint involves the current state of debris mitigation and removal technologies. This paper will describe various methodologies for remediating both small and large pieces of space debris, while acknowledging one major caveat in that the colossal volume of research on debris removal remains in the theoretical realm. As of December 2007, **no** applicable technology has been tested under actual operating conditions for the purpose of space debris removal. While legitimate reasons exist for this dearth, this paper presents a framework in which a debris removal experiment can be considered. Without this critical forward step, space debris removal and supporting policies will likely stagnate.

Detection/Tracking

Space debris detection and tracking are integral to space debris elimination. Every elimination technology requires a supporting detection system in order to determine debris position, velocity and heading. Tracking systems are designed to keep records of information gathered from the detection systems and computers are used to generate real time space environment models. Currently, these models provide information that is used for space mission operations.

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[147] Lester, J.P. and J. Stewart. Public Policy: An Evolutionary Approach, 2nd Edition. Wadsworth, Belmont, CA. 2000.

The largest detection, tracking and cataloging system in the world is currently the Space Surveillance Network (SSN). The SSN is comprised of U.S. Army, Navy and Air Force ground-based radars and optical sensors at 25 sites worldwide.[148] The SSN currently tracks over 8,000 space objects of which approximately 93% represents space debris.[149] The SSN is limited to tracking space debris that is greater than or equal to 10 cm in diameter (?).

There are several space detection systems that are owned and operated by different countries around the world. Not all of these technologies operate as part of the SSN. For example, the United Kingdom and France both own and operate detection technologies outside of the SSN. The information sharing section of this report details how information sharing can improve the SSN and overall space situational awareness.

Each space detection technology has its benefits and limitations. Factors that limit detection capabilities are debris size, altitude and orbit. In order to improve detection capabilities, more sensors could be added around the world to reach higher degree orbits. The size of the radars used could be increased for better resolution of debris size. Also, a space-based detection system could be used to increase the detection range out to GEO.

Listed below are a few examples of detection and tracking technologies. The detection examples given include radar, optical and space base detection. The tracking examples given include NASA's LEGEND program.

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[148] United States Space Command <http://www.au.af.mil/au/awc/awcgate/usspc-fs/space.htm>

[149] United States Space Command <http://www.au.af.mil/au/awc/awcgate/usspc-fs/space.htm>

Detection Technologies

Figure 4: Haystack and HAX radars

Haystack and HAX radar. Operated by Lincoln Laboratories, the Haystack is NASA's main source for debris data ranging in size from 1 cm to 30 cm.[150] The Haystack (HAX) and the auxiliary HAX are high powered long range imaging radars that operate in a fixed staring mode to statistically sample orbital debris in the LEO environment. The Haystack and HAX radars are, respectively, X-band and Ku-band monopulse tracking radars located in Tyngsboro, Massachusetts at latitude of 42.6°.[151] **Figure 4** shows an aerial picture of the Haystack and the HAX radars. The Haystack is the larger of the two spheres in the picture. Although NASA uses Haystack for the detection of debris sizes from 1 cm to 30 cm, it is capable of detecting objects as small as 5 mm.

[150] "Orbital Debris Optical Measurements." NASA Orbital Debris Program Office. 29 April 2005. <http://orbitaldebris.jsc.nasa.gov/measure/optical.html/>. Accessed Fall 2007.
[151] Stokely, C. "Flux Comparisons from the Goldstone, Haystack, and HAX Radars." Orbital Debris Quarterly News. April 2006. <http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv10i2.pdf.> Accessed Dec. 27 2007.

The Goldstone radar is a 230-foot diameter dish capable of tracking a spacecraft traveling more than 10 billion miles from Earth.[152] It is located at the California Institute of Technology Jet Propulsion Laboratory in Pasadena, California. Goldstone radar acts as a transmitter and receiver to detect objects as small as 2 mm in diameter. **Figure 5** shows a picture of the Goldstone radar.


Figure 5: Goldstone radar

The MODEST or Michigan Orbital Debris Survey Telescope is an optical telescope used for detecting objects in space. Optical detection not only allows for the detection of objects in space, but can also determine the composition of an object via spectral analysis. The system is located in Cerro Tololo Inter-American Observatory in Chile at 30.2° S, 70.8° W and 2200 meters in altitude. MODEST primarily focuses its observations on GEO. **Figure 6**


Figure 6: MODEST

[152] Stokely, C. "Flux Comparisons from the Goldstone, Haystack, and HAX Radars." Orbital Debris Quarterly News. April 2006. <http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv10i2.pdf.> Accessed Dec. 27 2007.

shows a picture of the MODEST.[153]

The MSX or Midcourse Space Experiment satellite was launched on April 24, 1996. The MSX observatory is a Ballistic Missile Defense Organization project and is the first system to demonstrate the technology in space to identify and track ballistic missiles during their midcourse flight phase.[154] Throughout the project, the MSX provided the opportunity to observe man-made debris in LEO and GEO by searching known debris streams for unknown objects.[155]

Computational Tools

Tracking technologies are used to track and catalog space objects. In order to track objects in orbit, the object's heading and vector must be determined empirically or predicted by computer modeling. NASA has two orbital debris evolutionary modeling packages named EVOLVE and LEGEND. EVOLVE models in one-dimension and LEGEND in three-dimensions.[156] The European Space Agency has also developed an orbital debris reference model called Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) to analyze space debris flux and spatial densities.[157]

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[153] "Orbital Debris Optical Measurements." NASA Orbital Debris Program Office. 29 April 2005. <http://orbitaldebris.jsc.nasa.gov/measure/optical.html/>. Accessed Fall 2007.
[154] Moshir, Mehrdad "The Midcourse Space Experiment (MSX)" MSX Celestial Backgrounds. 27 Dec. 2007 <http://www.ipac.caltech.edu/ipac/msx/msx.html>
[155] Heyler, Gene "MSX Midcourse Space Experiment" MSX Midcourse Space Experiment. 24 April 1996 JHU/APL. 27Dec. 2007 <http://sd-www.jhuapl.edu/MSX/MSX_Overview.html>

[156] Mehrholz, D., L Leushacke, W. Flury, R. Jehn, H. Klinkrad and M. Landgraf. "Detecting, Tracking and Imaging Space Debris." EESA bulletin 109: Feb 2002. <http://www.esa.int/esapub/bulletin/bullet109/chapter16_bul109.pdf>. Accessed 27 Dec. 2007.
[157] "Computational Tools." European Space Agency. 04 April 2007. <http://www.esa.int/TEC/Space_Environment/SEMNW3SMTWE_2.html.> Accessed Dec. 18, 2007.

Information Sharing

Introduction

Sharing space data is vital to current and future Space Situational Awareness. There are disputes as to which types of information should be shared, but it is generally agreed that all entities, whether foreign governments or commercial ventures with space assets, can benefit from orbital element information. There are many different reasons for building space surveillance systems and these directly affect the information sharing environment. Programs such as the USAF Commercial and Foreign Entities (CFE) Pilot Program are currently providing orbital data and examining how other types of information sharing can occur.

The World Security Institute's Center for Defense Information (CDI) held a 2006 conference on approaches to shared situational awareness. In the conference summary, CDI lists a series of information sharing process-related challenges:

- The current email-based process for requesting data from the SSN is inconvenient, requires too much advanced notice, and does not provide for direct contact in the case of complex matters.
- U.S. military SSN chain of command changes complicate interactions among stakeholders.
- Orbital data reporting formats and predictive models differ and are inefficient for broader community use.
- There is a lack of agreed upon reporting standards and interfaces for translating between formats and predictive models.

- Classification of orbital data and the "culture of secrecy" in military intelligence communities hinder the useful sharing of information. This is especially true when referencing intergovernmental communications.
- All satellite operators do not comply consistently with informal routines for reporting orbital data and maneuver information.
- Not all government operators participate in voluntary data reporting (i.e., China, Russia, and India).
- There are uncertainties with liability in regard to sharing orbital data for collision avoidance.[158]

While there is much debate as to whether the aforementioned challenges are actually problems, there are nonetheless continual calls for standardization of processes and increased sharing of information. A common information sharing system might alleviate some of the process-related challenges listed above and has the capability to adapt as information needs among governments, commercial interests, and even the casual space observer change as sensing and debris modeling technology changes.

Commercial and Foreign Entities (CFE) Pilot Program

The United States is looking to solve some information sharing issues with the Air Force Space Command's CFE pilot program. The objective of this project is to "determine feasibility/desirability of providing space surveillance data support to non-United States Government entities."[159] As part of the program, the website www.space-

[158] "Improving Our Vision: Approaches for Shared Space Situational Awareness." World Security Institute Center for Defense Information. 2006. <http://www.cdi.org/PDFs/SSAConference_screen.pdf.>. Accessed Oct. 29 2007.

[159] Maloney, Dave. "Space Surveillance Support to Commercial and Foreign Entities (CFE) Pilot Program." 20 Oct. 2004.

track.org was developed to provide a means of distribution for Department of Defense space surveillance data. This site provides a catalog of space debris objects in the form of Two Line Element (TLE) sets. The site includes information on satellite decays, bulk TLE downloads, satellite search capabilities, catalog change queries, and satellite and debris reports. See Appendix F – Space Track for more information.

The CFE program, set to expire in 2009,[160] is also exploring how it can provide other services:

- Conjunction Assessment (CA). CA determines the likelihood of a conjunction between orbiting objects. This includes screening for planned maneuvers
- End-of-life (EOL) support. Includes re-entry support and planned de-orbit operations
- Anomaly resolution support. Includes altitude determination, spacecraft configuration
- Emergency service. Emergency support is required when significant mission degradation or failure threaten either the requester asset or U.S. government assets, endangerment of human life, or degradation of U.S. national security. This is a free service[161]

The orbital element sets are presented as Two-Line Element (TLE) sets which are currently shared at lower accuracy than collected. A separate, high accuracy catalog is

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<http://celestrak.com/NORAD/elements/notices/Space_Surveillance_Support_to_CFE_Pilot_Program_V07.pdf>. Accessed Nov. 18 2007.

[160] United States. House Oversight and Government Reform Commitee, Subcommittee on National Security and Foreign Affairs. “Testimony for the Record of David McGlade, Chief Executive Officer, Intelsat.” 23 May 2007. <http://nationalsecurity.oversight.house.gov/documents/20070523163944.pdf>. Accessed Fall 2007.

[161] Maloney, 2004.

kept by the Air Force Space Command, which is used within DOD/NASA for conjunction assessments.

There is little incentive for a commercial entity to build its own space surveillance network. With information currently provided at zero cost, there is no profit potential to reward commercial entrepreneurship. Instead, commercial entities are strongly encouraging governments such as that of the United States to continue publishing orbital element sets. In a statement to Congress, Iridium Satellite, the operator of the largest commercial satellite installation in the world, stated, “We encourage continued funding of the Commercial and Foreign Entities (CFE) pilot program to provide space surveillance data to commercial operators to help promote safe operations in space.”[162] Some space operators within the commercial sector believe that the TLEs provided through the CFE program are not good enough. David McGlade, the CEO of Intelsat, has stated, “Although CFE has been advantageous for governments and industry, the accuracy of the data currently provided is not sufficient for precise collision detection/assessments, support of launch operations, end of life/re-entry analyses, nor anomaly resolution.”[163]

Foreign entities may decide to build separate space surveillance systems for many reasons. Space surveillance technologies can be seen as a source of national pride and relying on the United States could be interpreted as a source of weakness. It is commonly known that the element sets distributed through www.space-track.org do not include sensitive U.S. Satellites. This information, combined with the knowledge that website

[162] United States. Committee on Oversight and Government Reform, Subcommittee on National Security and Foreign Affairs, United States House of Representatives. Hearing on Weaponizing Space: Is Current U.S. Policy Protecting our National Security. Statement for the Record: Iridium Satellite, LLC. 23 May 2007. <http://nationalsecurity.oversight.house.gov/documents/20070523164435.pdf> Accessed Fall 2007.
[163] McGlade, 2007.

data is less accurate than available internal data, could lead to distrust of U.S. data. Users may also worry that the United States could purposefully modify the data for political reasons. A clause of the space-track.org User Agreement states, “The U.S. Government reserves the right, without notice and in its sole discretion, to terminate the user's access to this website, and to block or prevent future access to and use of the website.”[164] The potential that the CFE program could be abruptly terminated or discontinue publishing element sets to certain individuals is another reason that a foreign entity would build its own system.

As noted above, a desire for higher accuracy data than currently provided may drive a foreign entity to create its own space surveillance system. Debris modeling is only as accurate as its source information and beginning with low-accuracy data prevents high-accuracy modeling. A country may also use space surveillance as a bargaining tool in order to remove its sensitive satellite data from published element sets. France is a good example of this. The United States regularly publishes the element sets from French military and communication satellites. France claims to have used its Graves radar to track objects which are nonexistent in the SSN catalogue. According to these established agreements, they would like to get additional information on the 20-30 objects which they are tracking possibly use them as leverage to convince the United States that it should stop publishing data on the sensitive space assets of France.[165]

CFR program goals including providing orbital information, performing conjunction assessments for free or at a price lower than charged by a competing system,

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[164] “User Agreement.” Space-Track: The Source for Space Surveillance Data. 2004. <http://www.space-track.org/perl/user_agreement.pl>. Accessed Dec. 29 2007.
[165] deSelding, Peter B. “French Say 'Non' to U.S. Disclosure of Secret Satellites.” Space News 08 Jun. 2007. <http://www.space.com news/060707_graves_web.html>. Accessed Nov. 18, 2007.

and providing emergency services eliminate some of the incentive for other countries to make large investments in space surveillance. If the U.S. government were to begin sharing higher accuracy data with entities that can demonstrate their "need to know," yet another incentive to compete would be removed. Sharing higher accuracy information with certain entities is possible through the use of bilateral agreements. Creating levels of data sharing based on agreements would provide the ability to display differing accuracies of data to entities. The possibility of gaining access to higher accuracy data provides an incentive for the foreign entity to share its data as well. This is a more proactive approach than simply hoping that foreign entities will provide voluntary reporting. For instance, a close space ally would be able to receive data on orbital elements that is more accurate than a non-ally receives or that a non-official readers could view. The aforementioned reasons for countries to create their own space surveillance data are not all obviated by these services.

European military officials have argued that Europe needs its own space surveillance network to verify U.S. data and supplement it if necessary.[166] Commander of the French Air Defense and Command Patrick de Rousiers, believes that the Graves radar can be a complement to the space-track.org information. Rousiers claims that the Graves radar has proven its usefulness to France when it was used to verify the Chinese ASAT test.[167]

If foreign entities continue to add to their space assets and SSA deterrence measures are unsuccessful, they will likely also improve their space surveillance abilities.

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[166] deSelding, Peter B. "ESA Eyes European Space Surveillance Network." Defense News. 8 Oct. 2007. <http://www.defensenews.com/story.php?F=3077260>. Accessed Nov. 11, 2007.
[167] de Rousiers, Patrick. Strategic Space and Defense Conference 2007. Qwest Center, Omaha. 10 Oct. 2007.

It would be in the best interest of the United States to consider accepting data from outside entities. The CFE pilot program is examining how to provide data, but it is not looking at ways to accept and interpret information coming from commercial or foreign entities. There are many potential benefits in using commercial or foreign data.

Foreign Data

Deputy Director, Air, Space, and Information Operations, Air Force Space Command, Brian Wilson comments that the current gaps existing in SSN coverage and the geographic disbursement of current sensors of international entities alone should be sufficient cause to examine the potential benefits of using foreign data.[168] This additional geographic perspective may be able to provide for an early warning on a debris-causing event or simply to verify information received from the SSN. It may also be possible to better characterize the debris environment by filling gaps in SSN coverage with foreign data.

Accepting foreign data would allow the U.S. to gain a better understanding of what the foreign country is doing with their space surveillance technology. The SSA capabilities the entity is publishing can be compared with other intelligence on their space surveillance technologies such as cost or research projects for additional knowledge. Further, in the improbable situation of an SSN outage, a backup system may prove beneficial. Partial outage of any single sensor, even if due to maintenance or upgrades, may not affect the overall space picture but could create a gap in coverage.

Several arguments against using foreign space surveillance data have been made. One of these is that the overseas systems currently available are not as capable of

[168] Wilson, Bruce. Personal Interview. 15 Nov 2007.

tracking debris as the SSN. While this holds true today, it may not be the case in the future and the geographic locations of the sensors alone may provide additional information which is not currently available to the SSN. Another objection is that the data from foreign entities cannot be trusted as an entity could publish false data. However, accepting information from a variety of sources with differing levels of trust provides an opportunity to make decisions based on all available information. Others argue that examining foreign data is a waste of time and resources because the data either does not contribute positively to situational awareness or the data is wholly unreliable. This may be the case with current technology, but implementing a standardized system of information exchange and policies on how to deal with the information allows for adaptation as foreign sensors become more capable.

Conclusions

The CFE program is a good start in making orbital data available and a program such as this must continue, but a strategy to handle foreign data should be pursued. As space surveillance technologies continue to advance, the sharing of the data contained within the systems should be considered a top priority. Although the United States has the best space surveillance capabilities at present, this may not always be true. Integrating currently used or near-term external sensors with the SSN could increase the overall SSA picture.

Prevention

The first priority in resolving the space debris problem should be to minimize the amount of debris produced in orbit right at the start. The issue can be likened to pollution.

Though there are many available methods to help keep the environment clean, the first one that comes to mind is minimizing the amount of pollution that is produced in the first place.

Simply put, the idea is to keep things clean to begin with so that a major cleanup can be avoided later. Spending a small amount of time now devising and emplacing methods to lower production of debris can help avoid a much larger problem at a later date. It is less difficult and more cost effective to keep the environment clean by avoiding brash use of it rather than vigorously cleaning it periodically once it has been polluted.

The debris population is increased due to two main factors.. First, launch vehicles and satellites tend to leave small pieces in orbit that add to the total debris population. Second, these satellites and launch vehicles themselves become large debris by staying in orbit after their utility has ended. Both of these types of debris can be reduced by altering the design and functionality of future satellites.

Composition

When a satellite is launched many pieces are discarded. Some of these fall to earth and burn up and some portion must stay in orbit. Multiple stage rockets are currently used to launch satellites into space. The lower stages fall back to earth quickly, but the upper stages are jettisoned at a higher altitude and tend to stay in orbit for some time. The stages are held together with pyrotechnic fasteners. “Dozens of bolts and nuts hold together a spacecraft's rockets and rocket stages. When a rocket or rocket stage has used up its fuel, a device sends an electrical signal to a power cartridge that explodes. For most models, the explosion sends hot gases into the fist-size nut, splitting its threads and

releasing its grip on the bolt."[169] These bolts are released into space and can remain in orbit for a prolonged period of time.

Once a satellite has reached its intended orbital slot, it must deploy its sensors and solar panel array. The solar arrays are kept in place by tie-downs, which are released upon deployment. The sensors also have covers, such as lens caps, which are also released into orbit.

Once a satellite has reached the end of its operational lifetime, it can continue to produce debris. The space environment is harsh so; satellite designers make satellites that can withstand this environment while in operation. However, satellites often begin to degrade after their designed lifetime has passed. Small debris can be generated by radiation, micrometeorites and erosion due to atomic oxygen.

The production of debris would be lowered if certain standard practices were put into place. Using improved covering and longer-lasting paint could prevent degradation of the satellite and the production of small debris.[170] If satellites were designed to have fewer detachable pieces, there would be less debris produced during launch and deployment of instruments. With current technology, some detachable pieces must be used, but this drawback can be overcome. Fragments from pyrotechnic fasteners could be captured before they ever leave the satellite so that they do not strike any other space-faring bodies. In order to reduce the risk of the debris colliding with any satellites, the

[169] NASA Explores: Express Lessons and Online Resources. <http://nasaexplores.com/show2_912a.php?id=01-032&gl=912>. Accessed Oct. 2007.
[170] "Technical Report on Space Debris." 1999. Text of the report adopted by the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space, New York. <http://www.unoosa.org/pdf/reports/ac105/AC105_720E.pdf>.Accessed Fall 2007.

smaller detachable pieces could be attached to their parent body. These attached parts would follow the satellite and could be disposed of along with the satellite post-mission.

Removal from Orbit

After a satellite or rocket has served its purpose and is no longer useful, it remains in orbit, adding to the debris population. These objects tend to be large and thus easily trackable and avoidable. However, moving to avoid debris is costly. Any fuel used by a satellite to avoid debris is fuel that cannot be used for station keeping so moving to avoid debris decreases the useful lifetime of a satellite, costing the operator money.

Satellites and rocket bodies left in orbit pose another threat as well: disintegration into smaller pieces of debris. If the body is struck by another piece of debris, smaller pieces can be broken off and sent sailing into space. A large body can potentially become thousands of smaller pieces, each capable of wreaking havoc on anything in its path. Though these smaller pieces are not as deadly, they tend to be more difficult to track and pose a greater threat.

Rather than leaving these bodies in orbit and adding to the overall debris population, they can be moved at the end of their useful lives (EOL). The body can be moved into a so-called graveyard orbit or be de-orbited altogether. This can be done using a number of methods, including using thrusters, electrodynamic tethers, or even balloons with a large surface area.

De-orbit

In LEO, the most effective way of disposing of a satellite or other large body is to lower its altitude so that it will be rapidly de-orbited. Lowering the body significantly

increases the drag experienced, since the density of the atmosphere tends to increase as altitude is decreased. Increased drag causes the body to slow down more rapidly, thus lowering its orbit further until it is burnt up in the atmosphere or falls back to earth.

Currently, standard practice of U.S. agencies is to lower the orbit to 600 km, so that the satellite will de-orbit within 25 years. This is a step in the right direction, but more could be done. While having the satellite out of orbit in 25 years is surely better than having the satellite come down hundreds of years later, 25 years is still a significant period of time for a derelict object to be in space. Another downside of the current approach is that not all agencies are required to abide by this practice. Many bodies are left in an orbit and will not be coming down anytime soon.

Disposal Orbits

In upper orbits, it is more expensive to de-orbit a body as a much higher delta/change (Δv) is required. This equates to a higher fuel requirement, which means either a shorter operational lifetime or a higher launch cost due to the weight of the additional fuel. Keeping this in mind, there is another option to manage bodies in orbit. They can be placed in disposal or graveyard orbits.

A disposal orbit is an orbit which isn’t used for anything else and has become a sort of space junkyard for old satellites. These orbits are easier for satellites at higher altitudes to reach, so this can be a more cost effective way for operators to dispose of satellites. The debris in this area poses less of a threat, since its orbit does not intersect with the orbits of satellites still in use.

However, this method is not foolproof. Eventually, any debris in a graveyard orbit will decay into a lower orbit and possibly collide with other objects. Also, any craft that

passes through a disposal orbit is vulnerable to collision. A heavily populated disposal orbit can become a barrier to passage into higher orbits. A high population of debris in a particular area can also lead to more frequent collisions, thus sending smaller pieces of debris in many different directions.[171] This debris may be too small to track and could penetrate nearby orbits that are used for satellites.

Thrusters

The most obvious method for de-orbiting or moving a satellite to a disposal orbit is to use the same method it uses for station-keeping. Satellites slowly move toward the earth over time due to the effects of atmospheric drag. In order to combat this effect, satellites are equipped with thrusters to correct the orbit. Without these thrusters, a satellite will eventually move from its designated position and no longer be of use.

These thrusters can be used in order to move a satellite to a very low altitude orbit so that it will de-orbit quickly or to a disposal orbit where it will be out of the way of other bodies. Of course, this action requires fuel, so some of the satellite's fuel must be saved for movement at EOL. This is a simple enough solution, but isn't the most attractive option financially, since it shortens operational lifetimes and decreases earning potential. To increase the lifetime of a satellite, it could be launched with more fuel, but this increases cost as well. Extra fuel is expensive and the heavier launch weight increases the cost of sending the satellite into orbit.

Better construction along with improved design can save a lot of trouble in the future. If design modifications are made now that effectively reduce the amount of debris

[171] Jenkin, A. B. and R. A Gick. "Dilution of Disposal Orbit Collision Risk for the Medium Earth Orbit Constellations." 13 May 2005. Aerospace Corporation, Defense Technical Information Center, El Segundo, CA.

produced, the total amount of debris in the future will decrease over time, rather than increase.

How debris is managed will be strongly influenced by the cost of a particular solution. Cost/benefit analyses must be undertaken to determine if current practices should be changed and whether a particular solution should be used. Benefits in the sense of cost avoidance should reflect not only the immediate risk of collision, but also longer term problems associated with debris. This information can be used to properly balance the amount spent on debris mitigation and the risk of damage due to debris.

Eliminating Rocket Bodies

Abstract

In order to launch a satellite, a launch vehicle such as a rocket booster is needed to propel it into an appropriate earth orbit. There are many different types of launch vehicles that operate in many different ways. For simplicity, the basic design and operation of a rocket booster launch vehicle is described below. The basic rocket booster design consists of a single primary multi-stage liquid fueled rocket and optional secondary solid fueled rockets for added lifting power. The secondary rockets, also known as motors, can be seen in **Figure 7** in the lower portion of the primary rocket.

If all goes as planned, once the launch vehicle engines have been engaged, the engines will exhaust all of their fuel. A launch vehicle is typically designed with enough fuel to place its payload, in most cases a satellite, into a transfer orbit where the payload then propels itself to the final operational orbit. In the final stages of the launch vehicle's operation, it exhausts its remaining fuel and detaches from its payload to drift in space.

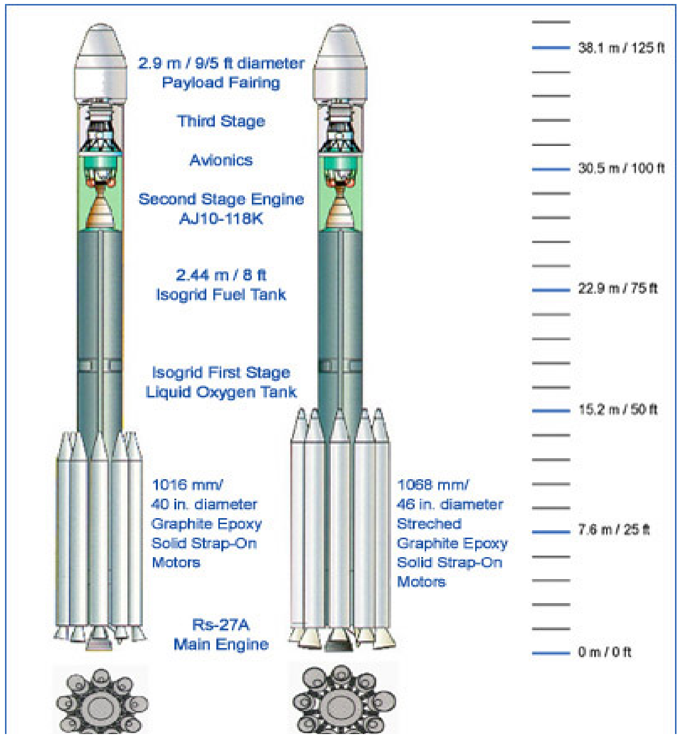

Figure 7: Technical drawing for a Delta II 7925 & 7928-H

While drifting through space, the final stage of the launch vehicle poses a threat to other objects in space. Objects at risk are space assets such as orbiting satellites, the ISS, the space shuttle, and future launch vehicles. Also at risk are other derelict rocket bodies and space debris. If rocket bodies are left to drift in space, they could collide with orbiting space debris and effectively transform a single orbital risk into a many smaller orbiting risks, thus increasing the overall threat to space assets.

Research

There have been extensive research efforts and testing aimed at preventing upper rocket body stages from remaining in space after EOL. One such test was performed on a Delta IV medium upper stage rocket. The Delta IV medium upper stage performed a

controlled de-orbit after delivering a satellite to its mission orbit.[172] The controlled de-orbit was required as the Delta IV went beyond its predecessor's performance and placed the payload directly into operational orbit. While placing the payload directly into operational orbit alleviated the need to make final payload maneuvers, it left the upper stage of the Delta IV at an altitude that would pose a risk to orbiting space assets. Adding to the challenge was the fact that the projected de-orbit time for the Delta IV exceeded U.S. Government Orbital Debris Mitigation Guidelines, which call for a maximum orbiting life of 25 years.[173]

Typically, the upper stage of the Delta IV performs a contamination and collision avoidance maneuver to lower its perigee and move the stage out of the payloads orbital plane so as to minimize risk.[174] To perform such a maneuver, the Delta IV would have used some of its remaining propellant to send it to a lower orbit. Unfortunately, such a maneuver was not possible due to another U.S. guideline violation as the upper stage was in violation of the casualty expectation value guidelines which provide that all re-entering spacecraft and upper rocket stages must have a casualty expectation value equal to or less than one in 10,000 per re-entry event.[175]

Due to the two violations, something different was required of the Delta IV upper stage. Fortunately, there was enough propellant left for de-orbiting, but this may not always be the case. If the Delta-IV upper stage hadn't enough propellant left to make the

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[172] Patera, R. P., Bohman, K.R., Landa, M.A., Pao, C., Urbano, RT, Weaver, M.A., White, Capt D.C. "Controlled Deorbit of the Delta IV Upper Stage for the DMSP-17 Mission" Space Safety in a Global World. 14 May 2007

[173] Patera, R. P., Bohman, K.R., Landa, M.A., Pao, C., Urbano, RT, Weaver, M.A., White, Capt D.C. "Controlled Deorbit of the Delta IV Upper Stage for the DMSP-17 Mission" Space Safety in a Global World. 14 May 2007

[174] Ibid

[175] Ibid

de-orbiting maneuver, under present conditions the choice would have been to risk it falling to earth or a collision with a space asset. Neither of these choices can be considered acceptable. A complete solution would be to de-orbit all rocket bodies after they have delivered their payload. This solution is detailed below.

Development

In order to develop a solution that de-orbits all rocket bodies after they have delivered their payload, the components needed to complete such a system should be established. The first and most direct component is the additional fuel needed in the upper stage. To include additional fuel in the rocket, the additional weight must be considered. Any weight added to a rocket will increase launching costs. Also, the total weight that a launch vehicle can carry into space is fixed because of current launch vehicle technology. The addition of de-orbiting fuel would require a corresponding reduction in payload weight or life expectancy of the vehicle. Second, current control circuit technology isn't considered reliable, therefore more research is needed to improve this technology.

Demonstration

In order to demonstrate a launch vehicle with an upper stage that can be de-orbited immediately after detaching from its payload; the system would need to be tested in the field. As was performed with the controlled de-orbit of the Delta IV upper stage, a similar demonstration should be carried out and analyzed for efficiency, functionality and effectiveness.

Conclusion

As mentioned in the debris origins section of this paper, the current space debris population consists of 16.6% rocket bodies. With the demand for space based technology increasing as a result of the internet, satellite television, global communications and the military, the number of rockets launched will also increase. Shown in **Figure 8** are predictions for the satellite population over the next four years. The graph gives three different scenarios for the number of new satellites launched over the given time period.[176] Comparing the three, new satellite numbers are different but the trend remains the same. The trend shows that after 2008/2009 the number of satellites launched per year will increase and the number of rocket bodies left in space will increase before reaching a high plateau around 2011. With each additional rocket body left in space, conjunction probability increases and existing space assets are at higher risk.

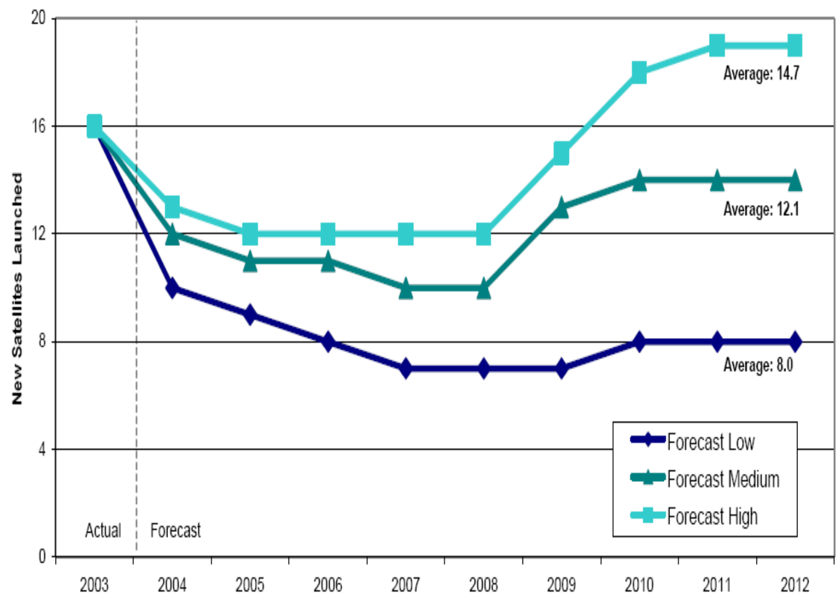

Figure 8: New satellite launch predictions up to 2012

If each rocket body were de-orbited immediately after detachment from its payload, this would reduce conjunction risk. The rocket would need to have fuel

[176] Futron Corporation. "How Many Satellites Are Enough? A Forecast of Demand for Satellites, 2004-2012." 16 Feb. 2004. <http://www.futron.com/pdf/resource_center/white_papers/Satellite_Forecast_2004_-_2012_White_Paper.pdf>. Accessed Fall 2007

allocated exclusively for de-orbiting it into the earth's atmosphere. The added fuel comes with added weight and, inevitably, added cost. Launching a satellite into space already has a high monetary cost associated with it. If the costs were to increase further, companies and governments might find it harder to cover it and the industry would be affected. From an industry perspective, increasing launching cost is not an acceptable solution. As a short term solution for the private sector, the added launching costs due to more fuel could be partly subsidized by the government. As a long term solution, further research is needed into cheaper rocket fuel and lighter weight rocket body and satellite fabrication materials.

Technology Rating System

Introduction

The space debris team rated existing technologies in order to compare removal techniques for similar sized debris. The rating system contains three primary categories: practicality, scalability, and affordability. Affordability is further broken into four subcategories: development, construction, implementation, and operation. Each category is divided into ten levels, ranked one through ten, ten being the highest ranking. Some levels are defined so as to have specific qualities. Interposed levels are understood to have qualities between those of their nearest neighbors. For each technology, a ranking was compiled for every category based upon the literature review and reasonable correspondence with scientific experts. See Appendix G – Elimination Technology Rating System for complete rating information.

Practicality

Practicality is a measure of how well a particular technology will be able to perform its assigned task. If a technology is physically impossible, it is given a rating of one. A rating of five is given if the technology can be built but will have little impact. A rating of ten is given if the technology can be implement and will have the desired effect.

Large area debris collectors and space-based magnetic field generators were given very low ratings in this category because their application is limited and they would have to be prohibitively large to have the desired effect. It would be very difficult for large area debris collectors to absorb the kinetic energy of debris. A large area debris collector would need to be in the order of 10 km in size to impact the debris population. Maintaining a structure of this size or the power required for a magnetic field generator in orbit is not practical.

Electrodynamic tethers were rated very high in this category because they are a relatively simple device. Increasing the drag to a satellite to bring it down from orbit is a simple approach that can be applied by use of a tether.

Scalability

Scalability is the measure of the effect an increase in the amount of debris would have on the ability of the technology to perform and the cost associated with that increase. If the technology cannot adapt to a change in the debris environment, it was awarded a score of one. The ability of the technologies cost model to adapt is not measured until the technology is determined able to adapt to significant debris changes. If the technology can adapt to significant growth in debris and, cost is exponentially

associated with the increase in debris, a score of six is given. If the cost is linearly associated with the debris changes, a score of eight is given. If there is no increase in cost and the technology can adapt to significant changes in debris, a ten is awarded.

Large area debris collectors and space-based magnetic field generators rated very high in this category despite their overall low rating. This is because the limiting factor for both of these devices is the area of space they can impact. If the amount of debris increases, they are able to capture more debris and their effectiveness increases.

Space-based lasers and magnetic sails received comparatively low ratings in this category. With an increase in debris, the risk of any space-faring body being disabled by an unexpected piece of debris also increases. Magnetic sails and space-based lasers would be particularly sensitive to damage from debris.

Affordability of Development

The affordability of development is quantified by how much of the development work has already been completed. A score of one was awarded if the technology is only conceptual, with no research to support the technological design. After a formal study has been conducted, a score of four is given. Once individual components have been tested, the score is raised to eight. A score of ten is given if the technology is deployable without any additional research necessary.

Large area debris collectors and space-based magnetic field generators were rated low in this category because of the lack of developments in the ability to orbit a large power source or a large structure.

Orbital transfer vehicles and electrodynamic tethers have high ratings in this category because most of the components of these systems have already been tested. They are the closest to a complete system test to remove debris in orbit.

Affordability of Construction

Affordability of construction is an indicator of how expensive it would be to build the system needed for the removal technique. Cost-prohibitive technologies are given a score of one. If the technology can be funded with no impact on the budget, a ten is awarded. The only intermediate step defined is a seven for additional spending required.

Electrodynamic tethers are rated highest in this category. Their relative simplicity and small size allow for construction to take a negligible percentage of an overall mission budget. A Space-Based Magnetic Field Generator is given the lowest ranking because the system would be very expensive. The required power supply, the physical size of the system, and its complexity all contribute to making this option undesirable on a construction cost basis.

Affordability of Implementation

The scores in this category are based primarily on required research and development costs associated with new technology. A score of one is given if no pre-existing technology exists and everything must be built from the ground up. A five is assigned if a system can be put together with previously existing components along with some new ones. If the technology only requires slight modification to current equipment, a score of ten is given.

Ground-based lasers score high in this category because the necessary tracking and detection systems are already partially implemented. A Space-Based Magnetic Field Generator scored the lowest in implementation for the same reasons that it scored low in the construction category.

Affordability of Operation

Affordability of operation is measured by the portion of the initial expense that must be spent each year for operations and maintenance (O&M). A score of one is given if the initial investment must be duplicated annually. A score of ten would be awarded if there are no follow-on O&M costs.

Space systems including Space Based Magnetic Field Generators scored low in this category because of the inherent difficulties of operating a complex system in orbit. Ground-based lasers and relatively simple on-orbit systems like tethers scored high. Ease of servicing and lack of complexity are reflected in higher scores.

Conclusion

Electrodynamic tethers and ground-based lasers were the two highest scoring technologies, receiving ratings of 8.5 and 8.0, respectively. The strengths of electrodynamic tethers include affordability of operation, affordability of construction and practicality. This is because the tether is a relatively simple device compared to a satellite. Specifically, the tether does not require a fuel supply that needs to be provided initially or replenished, nor does it rely on moving mechanical parts that are subject to breakdown and may have to be replaced. Tethers are also conceptually simple devices

that have been shown to work. However, electrodynamic tethers had a fairly low scalability rating due to the risk of a tether being severed by debris.

Ground-based laser strengths include affordability of operation and of implementation. The ground-based laser is considered affordable to operate because O&M cost are minimal compared to the initial investment. It is considered affordable to implement because it is assumed that the laser would be constructed at sites already possessing the required optics and infrastructure. Weaknesses are affordability of development and of construction. More development is needed because not all of the ground-based laser individual components have been thoroughly tested. Considerable funding would also be required for the construction.

Elimination Technologies

Ground-based Laser

Abstract

Ground-based lasers (GBL) have been proposed as a solution to remove small debris (1-10 cm) in LEO. There are two main components to any laser removal system; a targeting system and the actual directed-energy device. With radar based tracking or high-sensitivity optics, debris of 1 cm diameter or greater can be detected and targeted. Once the debris has been located and targeted, it is hit with short pulses from a laser. The pulses vaporize or ablate a micro-thin layer of the object, causing plasma blow-off. The result is a dramatic change in the object’s orbit, lowering its perigee, reducing its orbital lifespan and allowing it to burn up in the earth’s atmosphere.

Opponents of a GBL system may argue that it could be used as an anti-satellite weapon. A GBL system is designed for small debris and only ablates a few layers of molecules from the surface of the object. It would take months of dedicated operation to de-orbit even a medium-sized satellite. This approach does, however, have the potential to blind certain sensors on a satellite, but this effect can be avoided with proper operating procedures at the device location.

Research

The most prominent study involving ground-based lasers for debris removal was co-sponsored by NASA and USAF Space Command and published in 1996. Deemed the Orion Study, after the mythological archer, it sought to determine the feasibility of using ground-based lasers to remove small debris from LEO. Sub-objective assessments included protecting the ISS and other assets in LEO to an 800 km altitude and protecting all Earth-orbiting assets to a 1500 km altitude.

Any debris within the appropriate size would be targeted for removal. With the sensor and laser co-located, when the sensor detects the debris, the laser begins hitting it in short pulses. The study determined the optimum strategy was to target debris and cause re-entry in a single pass. The alternative was to hit the debris over multiple passes, which would require tracking the new orbit of the debris after it was hit it by the laser initially, a much more complex procedure. The laser can begin firing when the debris rises to 30° above the horizon on an ascending pass and stops when it reaches the zenith.[177]

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[177] Campbell J. W. "Project ORION: Orbital Debris Removal Using Ground-Based Sensors and Lasers." Oct. 1996. NASA Technical Memorandum 108522. <http://ntrs.nasa.gov/search.jsp?R=584235&id=9&qs=N%3D4294952893.> Accessed Fall 2007.

The Orion study suggested that a near term system could remove small debris at altitudes of up to 800 km. This capability would be sufficient to protect the International Space Station from debris 1-10 cm in diameter. At present, this debris cannot be tracked and the ISS lacks shielding against it in any case. Many remote sensing satellites are also found within this altitude and would benefit from removal of space debris up to this height.. A longer term solution would entail a GBL system capable of removing debris up to 1500 km.[178] See Appendix H – Orion Study Laser Removal Options for further details.

A more recent examination of the Orion laser concept found that recent advances in picosecond (one trillionth of a second) laser systems make the Orion concept more feasible in that shorter pulses allow a laser with the same energy to exert more power on an object. The ability to use a lower energy laser also allows components to cool much faster and the laser can be fired much more frequently than a laser of similar power with longer pulses.

The Mercury Laser, being developed at Lawrence Livermore National Lab (LNNL), is a short pulse Yb:S-FAP (Ytterbium:Strontium-Fluoroapatite) laser that could be used to accomplish Orion's Orion. The Mercury Laser is currently being developed through LNNL's Inertial Fusion Energy program aimed at producing a high pulse rate fusion storage laser. A systems study with a Mercury-type laser will give a better indication as to overall feasibility with respect to costs, risks, and benefits. A current proposal involving use of the Mercury laser focuses only on debris removal and does not address the tracking, targeting, and beam-directing challenges. [179]

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[178] Ibid

[179] Early, James T. et al. "Space debris de-orbiting by vaporization impulse using short pulse laser." <u>High-Power Laser Ablation V</u> 5448 (2004): 441-449 SPIE. 16 October 2007 < http://spie.org/>

Another study currently in progress is examining some aspects of tracking, targeting, and beam-directing in addition to de-orbiting space debris. Being conducted by IAP, Quantron Ltd, and the IPIE, the project is evaluating techniques for controlling debris using lasers. According to Dr. Michael Valley, the study is not due to be released until 2008, but it is examining laser technologies in much more detail than the Orion study. [180]

Development

With respect to debris sensing capabilities, the Orion study suggests that a radar system similar to Haystack or an optical system similar to the one located at the Starfire Optical Range would be able to meet its requirements.[181] The study also suggests that bi-static radars may be able to detect the debris but further research is necessary. In each of the solutions involving lasers, tracking is not required since they involve only simple detection and target handoff to the laser.

Microwave radars such as Haystack, developed and operated by MIT Lincoln Laboratories, are proven technologies that have the potential to support a ground-based laser. A microwave radar solution also provides the ability to determine how the particle was affected after engagement. While Haystack does not have an ideal location for a laser as it is located in an urbanized area, a remote handoff capability would alleviate this problem. With remote handoff, the radar would be able to send information in near real time to the laser for engagement. This capability could be used to integrate data from any radar-based system.

[180] Valley, Michael. Interview via conference call. 20 Nov. 2007.
[181] Bekey, Ivan. "Orion's Laser: Hunting Space Debris." Aerospace America 35:5 (1997): 38-44.

Passive optics use light from the sun to illuminate the debris and uses high-sensitivity, high-resolution passive optics to locate it. Utilizing an existing passive optical system is much less expensive than building new radar systems. Unfortunately, a passive optical system is only able to operate in clear weather conditions at appropriate angles of the sun, which amounts to about four hours per day. Orbital assessments are very difficult to conduct with passive optical systems and the shortened hours of operation would extend debris removal time considerably. Since there are some objects which can be detected in visible light that cannot be seen with radar and vice versa, a passive optical system could be used as a complement to a radar system.[182]

Bistatic Detection is based on the idea that orbital debris is constantly being illuminated by communications between the ground and objects in LEO and GEO. As the commercial space industry grows and space communication increases, more space debris will be illuminated. A bistatic detection system could thus benefit from a large number of potential illuminators which are free of cost to the GBL.[183] The targeting acquisition conclusions of the Orion study are shown in the figure below.

Using the laser system itself to perform both acquisition/targeting and debris removal is another option. The Orion study determined the laser radar is feasible, but adds a great deal of complexity to the laser system. Unfortunately, this technology is not as mature as microwave radar or passive optics, so any such laser radar system would require a substantial investment in research and development.

[182] Campbell, 1996.
[183] Campbell, 1996.

Parameter	**Radar**	**Passive Optics**	**Bistatic System**	**Laser Radar**
Search	Bowtie	WideFOV	None	Defocus or Fence
Detection				
500 km	1 cm	1 cm	> 5cm	1 cm
1000 km	1 cm	1 cm	> 10 cm	1 cm
1500 km	2 cm	1 cm	> 20 cm	1 cm
Tracking	Yes	Yes	No	Yes
Discrimination	Excellent	Good	Unknown	Excellent
HandoverAccuracy	Excellent	Excellent	NA	Excellent
DamageAssessment	Excellent	Partial	No	Excellent
Utilization	24 h/day	< 4 h/day	24 h/day	24 h/day
Availability	Exists	Buildable	New	ORION
Cost	Low for Haystack High/New	Low for STARFIRE Moderate/New	Unknown	ORION+

Figure 9: Orion Sensor Conclusions

Demonstration

The technologies researched in the Orion study have never been demonstrated in a space debris elimination application. The study suggests that the approach could be tested using existing hardware for $17-34 million (in 1996) and further recommends that the laser be demonstrated at either the Starfire or AEOS sites, as well as tested using the Haystack radar remotely. Such a demonstration would help determine the precision of acquisition and targeting capabilities. The results could also improve cost estimates while demonstrating the feasibility of creating an 800 km or 1500 km altitude system for small debris removal.

Conclusion

The Orion study concludes that removing debris 1 -10 cm in diameter from LEO is technically feasible in the near term. The study showed that debris removal with the

Orion laser concept is less expensive than increasing the shielding of the ISS from 1 cm to 2 cm. There are some disagreements as to the abilities of adaptive optics to illuminate debris, so further analysis or a demonstration is needed. A physical demonstration with within Orion parameters would provide proof of concept. There should also be serious consideration given to including more recent laser technology advances such as the Mercury Laser as possible removal mechanisms. Ongoing work such as the IAA study and the IAP/Quantron/IPIE workgroup on debris removal techniques should provide updated cost numbers and give a better indication of the technical feasibility of a ground-based laser system. Ground-based lasers were given an 8.0 rating in our analysis based on relatively low operating costs and ability to remove a large number of small debris in a short amount of time.

At present, there is not enough damage caused to satellites in orbit due to debris to justify the costs of building a full-scale debris removal system. However, if debris models are determined to be overly optimistic with respect to natural de-orbiting of debris or debris-causing events such as the Chinese ASAT test continue to occur, a GBL is a feasible way to eliminate debris. A GBL is far less expensive to implement than including enhanced shielding on space objects. Although the Orion laser can be tested with government-furnished equipment, international cooperation should be strongly encouraged in developing a full-scale debris removal system. For example, the Russians have made significant progress in Orion-type technologies and "are eager to apply these to an international project."[184]

[184] Campbell, 1996.

Airborne Laser

An airborne laser is advantageous because an airplane can fly high enough to be above most of the atmospheric interference that makes aiming the laser difficult. An airborne laser prototype is under development by Boeing, Northrop Grumman, and Lockheed Martin for ballistic missile defense purposes. However, airborne lasers have several disadvantages. Maintaining the laser and providing power is more difficult then with a ground-based laser. This technology has not been further explored because advances in adaptive optics have made aiming ground-based lasers more practical.

Space-based Laser

A space-based laser would operate similar to a ground or airborne laser in terms of targeting and acquisition of targets. A space-based laser benefits from not requiring atmospheric compensation. Space-based lasers also require less energy per pulse due to greater proximity to the debris. A space-based laser device could also be used to affect debris in orbits other than LEO since it could be positioned in other orbits.

There are many challenges to implementing a space-based laser. Simply getting the laser device into space greatly increases cost as compared to a ground-based solution. Stabilization of the laser platform is difficult in any environment, especially in space. Firing a laser repeatedly thousands or hundreds of thousands of times requires a considerable amount of power and this power requirement complicates any space-based solution. For these reasons, the space-based laser received a rating of 4.5 out of 10 overall.

Large Area Passive Debris Collector

A large area passive system employs a large surface used for collecting space debris and will function by passively encountering the debris by means of orbital interception or coincidental collision. An example of an orbital interception would be when a passive system is placed in the path of a currently orbiting object with the intention of intercepting it. A coincidental collision occurs when a space-based system equipped with a large area debris collector is struck by space debris.

Even in the most densely populated regions of LEO, most objects greater than 1 cm in diameter are greater then 10 km apart. When traveling in an orbit that is a different direction then the debris, 10 km is not a great distance because relative velocity is high. However, in order to collect this debris relative velocity would have to be low or the collector would be destroyed or damaged. Thus, in order to remove debris effectively, the collector would need to be very large, on the order of 10 km in diameter or there would have to be more collectors placed in orbit than cost feasible.

Electrodynamic Tethers

Using tethers is another possible way to combat debris production. Electrodynamic tethers function by using the earth’s magnetic field and the ionosphere. A long conductive tether can be released from the satellite at EOL or attached to a body in orbit. This downward-facing tether moves along with the body through the earth’s magnetic field, inducing a current in the tether. This induced current sets up a magnetic field that opposes that of the earth, causing a drag force on the object and thereby decreasing its orbital velocity. Lower orbital velocity causes the body to be drop to a

lower orbit. After some time, the object will move into the atmosphere and be incinerated due to friction.

Conversely, the satellite can pass a current through an upward-facing tether to produce the opposite effect and raise itself to a higher orbit. This can be accomplished using current technology. Satellites routinely use solar cells to produce power for other purposes. This same energy can be used to produce a current and set up a magnetic field that pushes the satellite to a higher orbit. Current estimates for a tether system show that it would be very effective in most situations and would be significantly less expensive than using thrusters.

Research

The concept behind tethers is fairly simple, but there remain many questions about the reliability of these devices. Researchers have put together theoretical models and simulations in order to try to shed more light on how well electrodynamic or momentum tethers will perform in the space environment. In Table 1, the approximate de-orbit times of objects in various orbits with tethers is compared to the de-orbit time for objects without tethers.

Satellite Decay Times					
	Orbital Inclination				Average
Initial	0°	25°	50°	75°	Decay
Height (km)	De-orbit Time (days)				Times (years)
400	10	15	15	20	0.7
500	15	20	25	40	5.5
600	20	30	40	80	20
700	30	40	55	140	80
800	45	55	80	200	325
900	55	70	110	280	650
1000	70	95	140	375	2100
1100	95	125	185	-	3200
1200	120	155	230	-	5500
1300	140	185	280	-	7700
1400	170	220	325	-	10000

Table 1: De-orbit Times for Objects in Various Orbits with and without Tethers

Some have questioned whether or not a tether could survive in the orbital environment. The basic design uses a relatively thin tether, one that would be easily damaged by larger debris or micrometeorites. Several studies have concluded that tethers could survive in space long enough to complete their objective, but the design of such tethers would have to be “creative”.[185,186] Construction using multiple strands that are periodically interwoven would likely be sufficient and appropriate designs already exist.[187]

[185] Pardini, C., T. Hanada, P.H. Krisko, L. Anselmo, H. Hirayama. “Are De-orbiting Missions Possible Using Electrodynamic Tethers? Task Review from the Space Debris Perspective.” Acta Astronautica, 60: 10-11 (2007). 916-929.

[186] Pardini, C., Hanada, T., Krisko, P. H., “Benefits and Risks of Using Electrodynamic Tethers to De-orbit Spacecraft”

[187] Anz-Meador, Phillip D. “Tether-Debris Interactions in Low Earth Orbit.” Space Technology and Applications International Forum, Feb. 11-14, AIP Conference Proceedings 552 (2001). Ed. Mohamed S. El-Genk. Albuquerque, NM: American Institute of Physics, 2001. 525-531.

Development

In order for tethers to be viable in near space, several individual technologies would be required. Some of these technologies have been developed and demonstrated, while others require more research.

The tether must be designed so that it is lightweight, yet be both strong enough not to break under tension and able to survive a collision with small debris. Aluminum is both strong and conductive enough for this purpose as well are relatively inexpensive. The design of the tether should feature multiple interwoven lines as studies have shown that single lines tend to have short lifetimes unless they have large diameters. The idea of using many small strands to form a sort of net, such as the HoyTether™, is a viable option.[188] A tether built in this manner would be stronger than a thicker single line tether and weigh much less, thus being less expensive to use.

Electrodynamic tethers require an electrical connection to the plasma in space on both ends of the tether in order to allow a current to flow. Charge is easily gathered by a bare wire, but there is difficulty in releasing the charge on the other end. An electron emitter solves this problem by expelling electrons back into the ionosphere at the terminal end.[189]

Some method of controlling the tether while it is deploying and once it has fully deployed is needed as well. The various forces on the tether can cause it to swing or vibrate. This motion can increase the tension in the tether or lead to tether inefficiency. Control devices to manage this phenomenon are under development.

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[188] Forward, R. L., Hoyt, R. P., "Failsafe Multiline Hoytether Lifetimes"
[189] Cosmo, M.L. and Lorenzini, E.C., eds. Tethers in Space Handbook. 3rd Edition. Smithsonian Astrophysical Observatory. Prepared for NASA Marshall Space Flight Center, December 1997. <http://www.tethers.com/papers/TethersInSpace.pdf.> Accessed Fall 2007.

The method of deployment is a very important aspect of this technology. A tether that does not deploy properly is useless and can become dangerous to the any nearby spacecraft. However, these devices have been successfully used in the past as detailed below.

Testing

On March 29, 1993 and March 9, 1994, the Small Expendable Deployment Systems (SEDS-1 and SEDS-2) were launched. SEDS-1 successfully de-orbited a 25 kg payload from LEO by hurling it toward the earth using a momentum transfer. SEDS-2 demonstrated the use of a closed loop control law to deploy a tethered payload along the local vertical.

On June 26, 1993 the Plasma Motor/Generator (PMG) was launched into orbit at 890 km. The experiment involved lowering a 500 meter long conductive tether with electrodes at both ends into the thermosphere from a spent Delta upper stage. A current was produced in the tether, as predicted.

On June 20, 2006 the Tether and Physics Survivability (TiPS) satellite was launched into a nearly circular orbit at approximately 1000 km. The deployed system consisted of two end masses connected by a 4 km tether. The system successfully gathered information about gravity-gradient tether dynamics and tether survivability.

On September 25, 2007 the ESA’s second Young Engineers’ Satellite (YES2) was activated and released from Foton-M3 in LEO. A tether was deployed to 31.7 km and a small capsule, named Fotino, was released and sent back to earth. The Foton-M3

moved up 1.3 km in its orbit, as expected. This tether is the longest man-made object in space to date.

Demonstration

Though individual pieces of a tether system capable of moving satellites have been tested, the entire system has not yet been implemented. Most of the needed pieces exist, so this is definitely a near term technology. Once the needed parts are developed, tethers should be a viable substitute for extra thruster fuel in order to move EOL satellites and upper stages into more convenient orbits.

Momentum Tethers

Momentum transfer tethers function by transferring the momentum of one object to another by attaching and releasing the tether at specific points in the objects orbit. This cannot only alter the path of the bodies, but also speed one up while slowing down the other.

Rendezvous Debris Removal

Abstract

An active rendezvous space based removal solution is capable of changing orbits to pursue debris. Removing large debris such as failed satellites and spent rocket bodies removes the most mass from space with limited orbital changes.

This solution is limited by the amount of fuel that can be carried and by the complexity of the technology needed to execute it. Changing orbits requires a change in

velocity which uses the limited fuel supply. Fuel cannot be added without increasing launching cost.

The craft would rarely have to maneuver to avoid objects that it is not trying to remove because its surface area is relatively small. This decreases the chances of the craft being destroyed by debris coming from unexpected trajectories.

Traditional satellites rarely make orbit changes. Normally, one is made to enter orbit at the beginning of its life and one is made to move to a graveyard orbit at the end of its life. In contrast, an active debris removal craft would need to make orbit changes regularly. Attaching to another spacecraft without a human operator is difficult. In order to avoid collision in a close operating environment, the craft needs to be able to make timely decisions. For this to happen, the craft needs to be autonomous because the communication delay is too great to expect a ground operator to be able to make and implement decisions in a timely manner. Quality sensors able to give the vehicle an accurate depiction of its surroundings are also a priority due to the absence of an on-board human operator.

The orbits used around earth are not very dense so incidental conjunctions are rare. Actively pursuing debris offers the most efficient use of debris collecting equipment launched into space. 800 km to 850 km is currently the most densely populated region in LEO with a spatial density less then $2.5 \cdot 10^{-8}$ objects per km^3[190]. This translates into less

[190] Liou, J.-C., and Nicholas Johnson. "A Sensitivity Study of the Effectiveness of Active Debris Removal in LEO." (n.d). NASA Archives. <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20070013702_2007011170.pdfNASA> Accessed Nov. 2007.

then 1 object per 40 million km^3. On average, objects 10 cm or larger occupy a cube with sides of 342 km.

Research

At the basic level orbital changes are executed by speeding up or slowing down. Objects in higher orbits have slower velocities. However, objects in higher orbits have higher potential energy because they are farther from earth. To move from a lower orbit to a higher orbit a velocity increase is needed. The increase in energy from velocity is traded for an increase in potential energy as the orbit increases.

Coplanar Rendezvous is the simplest type of orbital transfer and uses a Hohmann Transfer. The interceptor will start in a lower orbit and needs to change its velocity twice, first to enter an elliptical orbit that is tangent to the target orbit and again to sustain the new velocity. Each time the interceptor will be increasing potential energy but decreasing actual velocity.[191] This is generally not accomplished in a single orbit, but over multiple orbits with corrections each time.

Co-orbital Rendezvous are accomplished by entering a phasing orbit that with an elliptical shape. The interceptor will first slow down to drop to a lower orbit. This allows the interceptor to orbit faster and catch the target. [192]

Launch weight limitations place limits on the amount of fuel that can be taken on-board. Efficient propulsion systems are necessary to travel between satellites. Ion thrust motors are most often used in orbit. They are very weak and produce very little thrust but are effective because there is negligible resistance in space.

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[191] Sellers, Jerry., et al. *Aerospace Science: The Exploration of Space*. New York: McGraw-Hill Companies, 2003.
[192] Ibid

The distance a satellite can travel before it runs out of fuel is measured by the total Δv budget. Δv refers to the change in velocity possible. Change in velocity is used as a measurement instead of distance because orbital mechanics dictate that an object traveling at a particular speed will maintain a particular orbit.

It is difficult to know the definitive gain from preventing collisions because they are difficult to study in space. There was only one satellite break up known to be caused by a collision which occurred between 1961 and 2003.[193] It is difficult to tell when collisions actually happen because we are unable to track small objects that are responsible for the majority of impacts.

A study of collisions from 1957 to 2035 was done by P. Krisko using NASA's LEO-to-GEO Environment Debris (LEGEND) model and is summarized in Table 2 below. "It was found that approximately 95% of all collisions occur between impactors that are smaller than 10 cm in size and targets that are larger than 10 cm in size, and 98% of these collisions are non-catastrophic."[194] One important reason that the number of collisions between targets less than 10 cm and impactors less than 10 cm is so few is because of the use of historical data. As of the date of this research, nobody has been able to study collisions between these small objects in orbit because the technology to study these smaller collisions has not been available.

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[193] Whitlock, David O. and Jer-Chyi Liou. History of On-Orbit Satellite Fragmentations, 13th Ed. May 2004. National Aeronautics and Space Administration Orbital Debris Program Office.<http://orbitaldebris.jsc.nasa.gov/library/SatelliteFragHistory/13thEditionofBreakupBook.pdf>. Accessed Fall 2007.

[194] Krisko, P. "Risk to LEO Spacecraft Due to Small Particle Impacts." Orbital Debris Quarterly News. 11.1: Jan. 2007. <http://www.orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv11i1.pdf>. Accessed Fall 2007.

Total period 1957 through 2035 (79 years)		
Ave # collisions	all	Catastrophic
Target < 10 cm, Impactor < 10 cm	1	
All	108	7
Target ≥ 10 cm, Impactor < 10 cm)	102	2
Target ≥ 10 cm, Impactor ≥ 10 cm	5	3

Table 2: Test summary events[195]

There were 1,744 pieces of debris cataloged from 1961 to 2003 reflecting unknown break-ups. From 1978 to 2003, there were 85 anomalous events that resulted in 262 pieces of trackable debris. Anomalous events are different from breakups because the separation is at relatively low velocity and the satellite remains relatively intact.[196] These are two types of debris-causing events that were possibly caused by collisions.

The amount of small debris created is difficult to account for using current U.S. tracking systems. Currently the best methods for predicting the amount of debris generated are from lab tests, simulations, and by looking at damaged space craft returned to earth.

In early 2007 three hypervelocity collision test were completed. The tests used three microsatellites that were each 20 cm x 20 cm x 20 cm and weighing 1.3 kg. The impacting objects were aluminum spheres 30 mm in diameter and weighing 40 grams

[195] Ibid
[196] "History of On-Orbit Satellite Fragmentations: Thirteenth Edition" NASA Orbital Debris Program Office. May 2004

fired at speeds between 1.6 and 1.7 km/s. 1,000 to 1,500 pieces of debris were collected from each test.[197]

In 2006, a similar study utilized two 15 cm x15 cm x15 cm microsatellites each weighing about 0.8 kg. One satellite was impacted at 1.5 km/s using a 3 cm diameter 40 gram projectile. The other satellite was impacted at 4.4 km/s using a 1.4 cm diameter 4 gram projectile. Each test generated around 1,500 fragments.[198]

Both of these tests were conducted with relatively small satellites. The average satellite in LEO has a mass between 600 and 700 kg. The average satellite in GEO has a mass around 1500 kg.[199]

As humans continue to increase the density of space debris around the earth, particularly at LEO, we risk higher collision rates. Hypervelocity collisions have similar effects to blowing up a satellite. There have been several experiments and simulations showing this. It is unlikely that removing large debris will have an immediate impact; however, simulations predict that debris created by collisions will be the dominate debris type in the future. By removing large masses of intact debris like rocket bodies, this likely will prevent increased numbers of collisions.

Development

Further developments in satellite robotic abilities will be necessary. The Front-End Robotic Enabling Near-Term Demonstrations (FREND) project will help improve

[197]Hanada, T., Sakuraba, K., Liou, J.-C. “Three New Satellite Impact Tests.” Orbital Debris Quarterly News. 11.4: October 2007 http://www.orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv11i4.pdf
[198]Hanada, T, Y. Tsuruda, and J.-C. Liou. "New Satellite Impact Experiments." Orbital Debris Quarterly News 10:3. July 2006. <http://www.orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv10i3.pdf>. Accessed Fall 2007.
[199] “Global Security.” 09 Sept. 2007. Union of Concerned Scientists, UCS satellite database. <http://www.ucsusa.org/global_security/space_weapons/satellite_database.html>. Accessed August 2007.

the robotic arms necessary to remove space debris. FREND is a Defense Advanced Research Projects Agency (DARPA) project currently under development.

Active debris removal vehicles are well equipped to act as servicing vehicles as well. Satellites could be repaired and thus not become debris. For the Orbital Express project Boeing developed a nonproprietary satellite servicing interface. ASTRO (Autonomous Space Transfer and Robotic Orbiter) and Nextsat were built at different locations and were still able to fit together. Further developments in standardization of satellite construction can promote the use of on-orbit servicing.

Testing

An autonomous control system is necessary. The communication delay from orbit to ground makes it very difficult to achieve the necessary precision. Autonomous control systems are currently used by the Russian *Progress* spacecraft to refuel the ISS.

A vision guidance sensor was developed by the Marshal Space Flight Center and used in 1997 on the Spartan. An advanced vision guidance sensor was later used on the Demonstration of Autonomous Rendezvous Technology (DART) and Orbital Express.[200]

Progress normally takes two days to reach the ISS. It is completely autonomous until it is 150 meters from the station at which point it is monitored and can be controlled from the ISS.

The DART space craft was designed to be completely autonomous. The system failed and the DART bumped into its target satellite. No damage was done and the DART de-orbited.

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[200] "Automated Rendezvous and Docking at Marshall Space Flight Center: Development Capabilities." National Aeronautics and Space Administration. 30 April 2007. <http://ard.msfc.nasa.gov/dc.html>. Accessed Fall 2007.

The Orbital Express consists of ASTRO and Nextsat. The project cost about $300 million.[201] ASTRO is an autonomous satellite servicing vehicle. It was controlled from the ground at the beginning with autonomous systems providing verification only. Later, confidence in the autonomous system was high enough for it to be allowed to take complete control. The control systems were able to transfer fuel between the two craft. ASTRO was able to replace the battery in the Nextsat as well as one of its own computers.

Demonstration

The following is a short list of spacecraft predicted or proven to have the necessary autonomous and orbital rendezvous tools to capture large debris.

- ATV (EAS)
- DART (US)
- STS (US)
- *Progress* (Russia)

Progress carries 1700 kg of supplies and has the ability to help with station keeping while attached to the ISS. After it is filled with 1700 kg of trash, it releases and burns up in the atmosphere. Assuming the Progress would have the Δv budget to make orbital rendezvous, it could be used to collect 1700 kg of debris before burning up in the atmosphere.

ASTRO has a robotic arm and a large enough Δv budget to make multiple rendezvous. However, its robotic arm attaches to a specially designed satellite. Other

[201] Young, Kelly. "'Mechanic' satellite looks under its own hood." NewScientist 02 Apr. 2007. http://space.newscientist.com/article/dn11511-mechanic-satellite-looks-under-its-own-hood.htm. Accessed Fall 2007.

robotic arms have been used and are being further developed. The Δv budget of ASTRO allows it to rendezvous with multiple space craft. During its mission the ASTRO was able to rendezvous with the Nextsat from a distance of 380 km.

Conclusion

The number of objects a craft like ASTRO could de-orbit is dependent on the mass of the objects and the amount of fuel the craft could carry. After four months of operation there was not enough fuel to safely de-orbit the Nextsat and ASTRO together.

Attaching tethers, which weigh far less then the fuel needed for controlled de-orbit, would allow masses to be de-orbited while saving weight on fuel. If tethers were unable to provide the necessary controlled re-entry, an ASTRO-type vehicle could be used to de-orbit an object safely. This would require that the vehicle be refueled in orbit. The ISS is currently using *Progress* to refuel as its fuel capacity is ten times that of ASTRO.

Active debris removal using orbital rendezvous vehicles scored 6.0 out of 10 in our rating system. Its strengths were practicality and affordability of development. This is because most of the necessary components of the system have been developed and tested. Its weaknesses were affordability of construction, implementation, and operation as the system is complex and requires orbital refueling.

Drag Augmentation Device

Another possible way to de-orbit a rocket body quickly is to increase aerodynamic drag experienced by increasing the surface area of the body. This can be accomplished by inflating a large balloon when the body is ready to de-orbit. At orbital altitudes,

atmospheric pressure is very low so a small amount of gas can occupy a relatively large area. A balloon could be deployed from or attached to the satellite and then inflated with gas. This gas can be the product of a chemical reaction or can be pressurized and stored on the satellite for later use. Since a gas-filled balloon could be ruptured by a piece of debris, some have suggested using expanding foam which later solidifies. This method would be helpful to avoid deflation but would most likely add to weight as a foam will be denser than a gas at low pressure.

This system could only be used for lowering the orbit of a satellite and not moving it to a higher one. Also, this method is more efficient in areas with higher atmospheric density, so is really only useful for satellites in LEO. The increased volume of the balloon-satellite system poses some concern, though such a large body could easily be detected and avoided.

Space Sail

Space sails include magnetic sails, electric sails, and solar sails. A space sail would be used to propel an object in orbit. Space sails were not explored further because they have a large surface area, are fragile, and could be damaged by space debris.

Space-based Magnetic Field Generator

Conceptually, a magnetic field could be generated by a satellite to attract debris in orbit. The magnetic field would attract objects with a charge. Magnetic fields weaken rapidly over distance so a very large magnetic field would need to be generated.

This idea was not explored further because the system is impractical, prohibitively complicated, and there was no research found on the topic. The power supply to generate

the required energy would need to be much larger then any currently in orbit. If the magnetic field worked and was large enough to pull debris toward the satellite, the debris hit the satellite at a very high velocity. As the debris comes closer to the satellite, the magnetic field would be stronger and would accelerate the debris. This would require the satellite to have a large amount of shielding, adding to weight and cost.

Overall Summary

Limitations

Research on space debris spans decades as well as national borders. The wealth of information, coupled with access to worldwide experts via our affiliation with the U.S. Strategic Command, provided a rich base from which to study the problem and recommend solutions. Several constraints should be noted. This project was limited in scope due to the time constraint of four months and a limited number of researchers. Furthermore, access was limited to only unclassified sources.

In order to provide solid recommendations, the research focus was narrowed in terms of both orbital scope and policy arena; delimitation of multiple orbits and a variety of political factors were necessary to maintain clarity.

Further Research

There are many aspects of space debris removals which this study has not examined or which have been only partially researched. The following list illustrates additional areas for research.

- Formulate a budgetary and diplomatic framework to move forward with technological demonstrations of debris removal.
- Research ways in which NGOs such as national labs and non-official space observers might productively share space data
- Determine status of the CFE pilot program and its information sharing capabilities

- Determine feasibility of using semi-structured formats like the eXtensible Markup Language (XML) for information sharing.
- Research related technologies to show how a ground-based laser would be able to target debris.
- Interview debris detection facility operators.
- Determine the current feasibility of Orion laser removal options since the project was completed over a decade ago

Overall Conclusions

Space debris threatens valuable space-based assets essential to communications, global commerce, and national defense. Debris in lower earth orbit poses the greatest immediate threat to these assets and was the primary focus of this project.

Policy is a critical consideration when introducing debris elimination technology into the space environment. Space-faring countries and commercial interests must acknowledge the inevitability of more numerous collisions and damage. If space debris continues to increase, the threat to space-based technology increases exponentially. Approval of space debris mitigation guidelines is a positive contribution to debris mitigation and prevention. In the short term, there is a need to clarify space terminology, define transfer-of-ownership guidelines, and create a registration timeframe to enhance the current body of space law.

As is evident with the IADC, international science-focused workgroups bring together researchers from various countries with varying interests to work on a common goal. Similar initiatives promise to improve debris mitigation/elimination efforts and improve upon current elimination technologies. As the world's dependence on space-

based technology grows, an evaluation of constructs for global pooling of funds earmarked for future debris clean-up will be necessary.

Prevention is the most cost effective way to keep space clean. However, prevention alone will not be enough to secure the future of space assets. The ability to remove space debris actively is imperative and there is no single solution to remove all debris sizes. Current technologies are promising, but further development remains necessary and no debris elimination technology has yet to be fully demonstrated. Ground-based lasers were found to be the most effective way to remove small debris from LEO. They are much more cost effective than adding shielding to space assets and a demonstration could prove the ability of lasers to remove smaller debris from space. Orbital rendezvous vehicles provide an example of a technology which could be used to remove large debris. The vehicles could be used to move the debris itself or used in conjunction with a drag device such as an electrodynamic tether to de-orbit debris or to place it in a graveyard orbit.

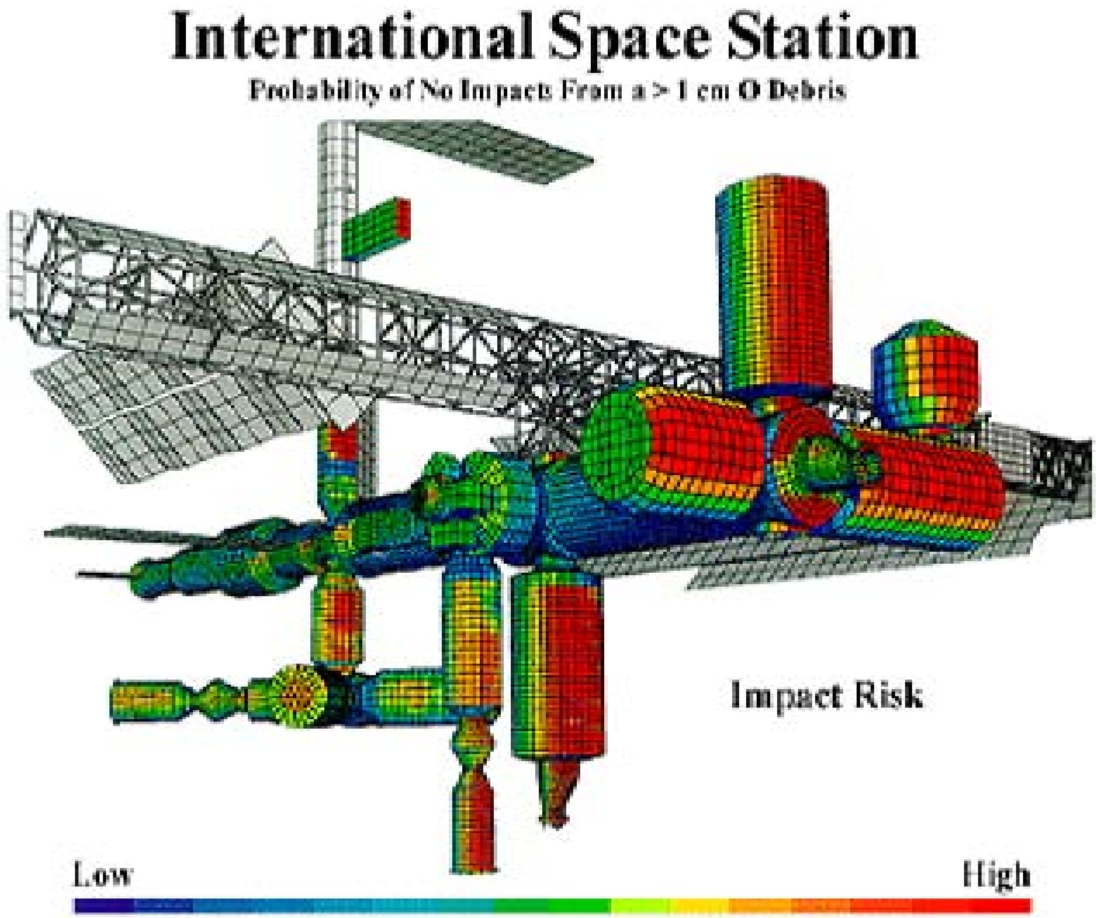
Policies specific to the recommended technologies require collective international ownership in order to realize a practical space debris elimination technology demonstration. Demonstrations are necessary to prove a technology’s ability to reduce the risk of debris collisions with space assets and all nations utilizing space-based technologies should contribute funding.

Appendices

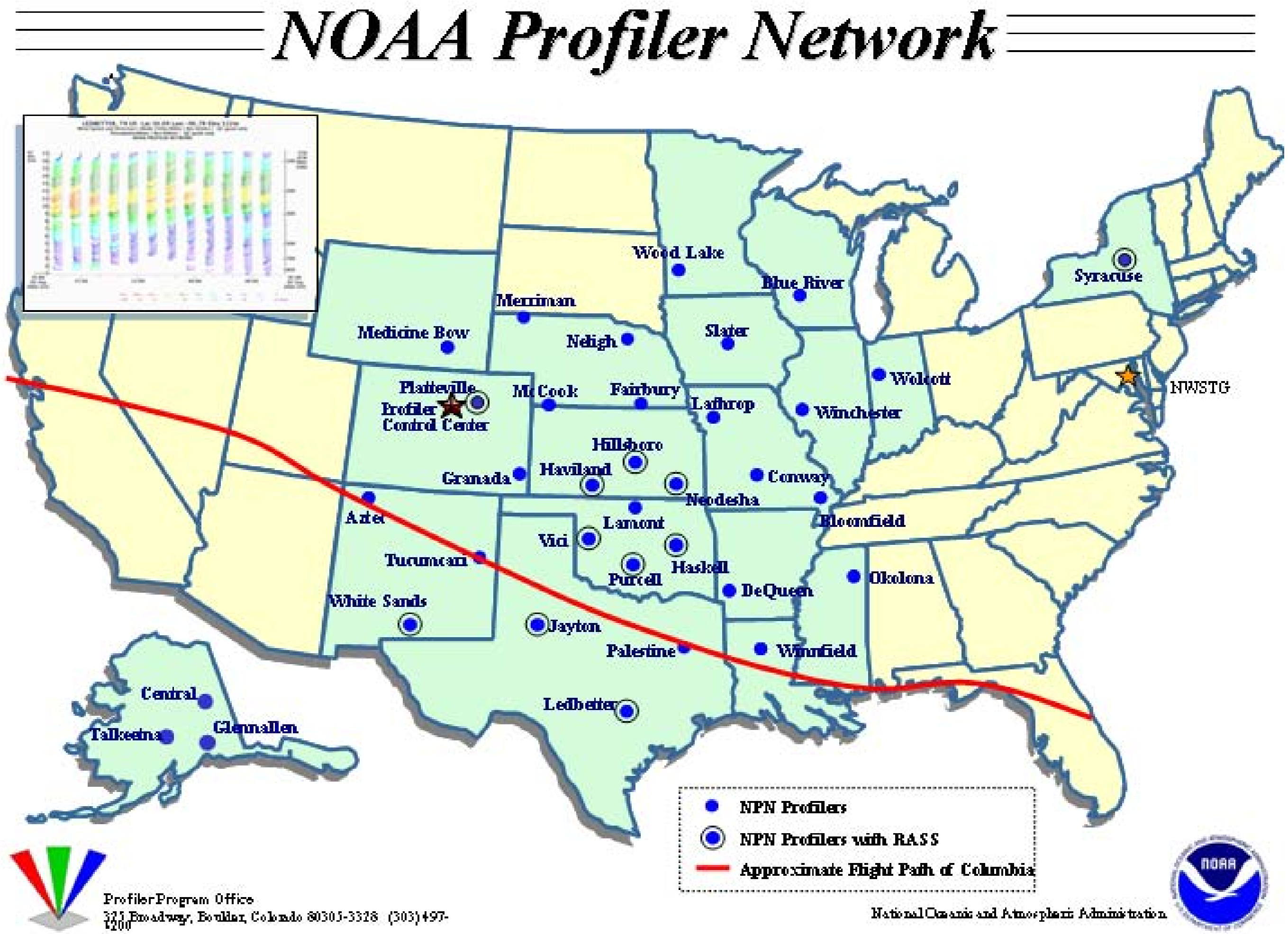
Appendix A – Long Duration Exposure Facility

The Long Duration Exposure Facility (LDEF) on orbit.
NASA Langley Research Center, Hampton, VA.

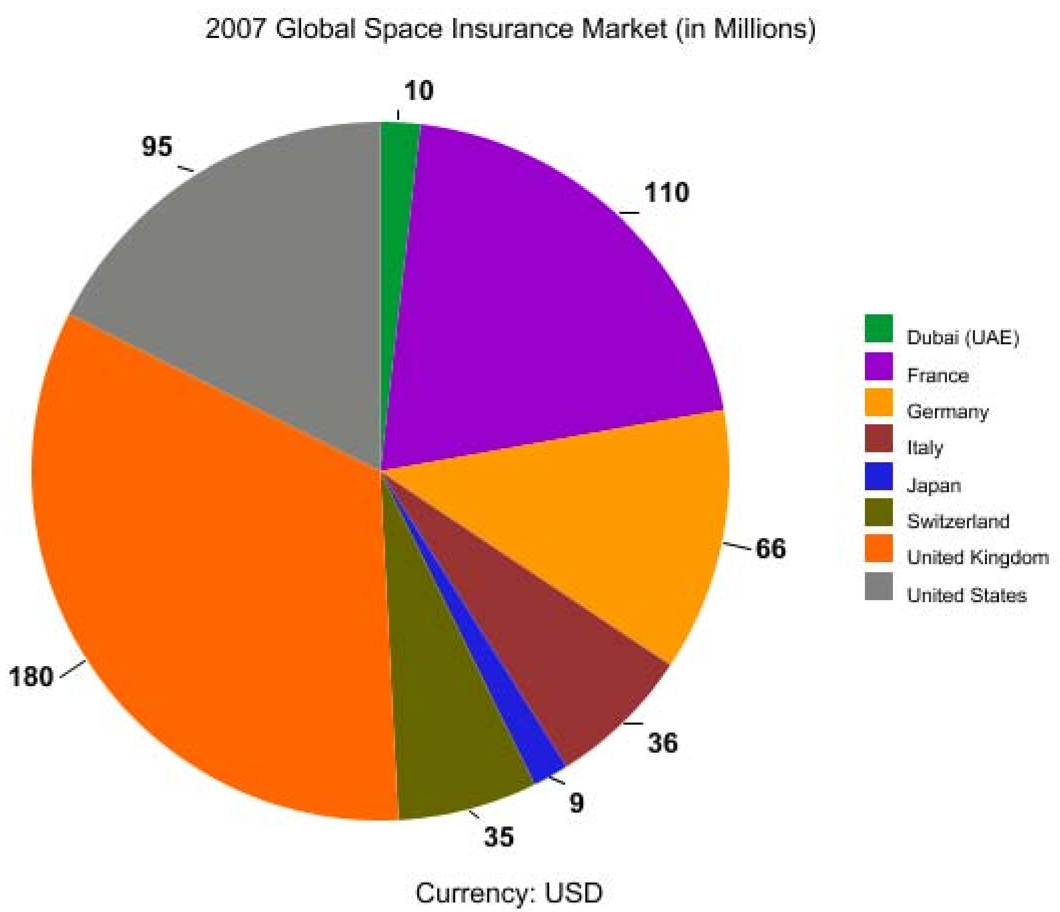
Appendix B – Impact Probability: International Space Station



Appendix C – NOAA Profiler Network



Appendix D – Global Space Insurance Market



Appendix E – Policy Analysis

Policy Tool	**Political Viability**	
	U.S.	*International*
Short Term		
New Treaty	0	0
Addendum to Outer Space Treaty of 1967		
Establish registration timeframe	5.0	4.5
Establish “transfer of ownership” guidelines	7.0	7.0
Terminology clarification within five agreements*	3.5	3.5
Science-based research groups	10.0	10.0
International debris elimination demonstration	8.0	7.5
Long Term*		
Commercial debris clean-up applications	5.0	5.0
Government Pooling of resources for clean-up	5.0	4.5

Political Viability Key

Establishes a conceptual political framework in consideration of current national/international space law, policies, and norms while allowing for the scope and complexity inherent in national/international relations.

10
Immediate, strong support likely
7.5
Support with time
5
Consideration likely
2.5
Possible consideration
0
Little or no support at this time

* The Outer Space Treaty of 1967, Registration Convention, Liability Convention, Rescue of Astronauts and Moon Treaty.
** Assuming economically feasible solution for debris clean-up and resulting market creation.

Appendix F – Space Track

Space Track Website

Space Track

The Source for Space Surveillance Data

Welcome to Space-Track

There are currently 64456396 TLE in the database
Last Update: Fri Dec 28 15:59:49 2007 GMT

Due to existing National Security Restrictions pertaining to access of and use of U.S. Government-provided information and data, all users accessing this web site must be an approved registered user to access data on this site.

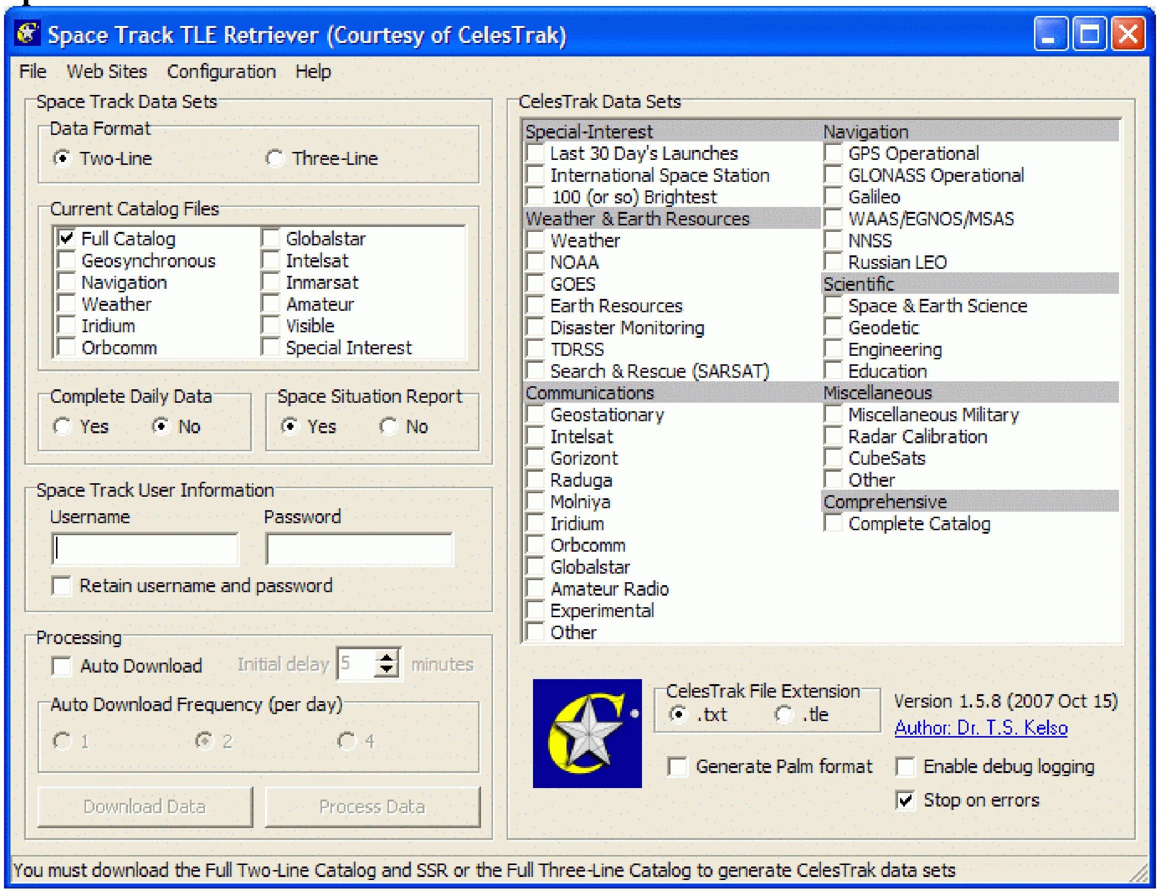
A Basic Description of the Two Line Element (TLE) Format.

In supported browsers, simply hovering your mouse pointer over a field in the sample TLE below will pop up a tool-tip style description of the field. Every field is also a hyperlink to the description table below.

```
ISS (ZARYA)
1 25544U 98067A   04236.56031392  .00020137  00000-0  16538-3 0  5135
2 25544  51.6335 341.7760 0007976 126.2523 325.9359 15.70406856328903
```

Source: http://www.space-track.org

Space Track TLE Retriever



Source: http://celestrak.com/SpaceTrack/TLERetrieverHelp.asp

Appendix G – Elimination Technology Rating System

Ratings

Debris Removal Technique	Practicality	Scalability	Affordability Development	Affordability Construction	Affordability Implementation	Affordability Operation	Overall Effectiveness
Ground-based Laser	8	8	7	7	9	9	8
Airborne Laser	7	7	7	5	7	5	6.3
Space-based Laser	5	4	5	3	2	8	4.5
Large Area Passive Debris Collector	2	10	2	2	2	8	4.3
Electrodynamic Tethers	9	7	8	9	8	10	8.5
Momentum Tethers	6	8	7	7	5	7	6.7
Capture/Orbital Transfer Vehicle	8	6	8	4	5	5	6
Drag Augmentation Device	6	5	6	7	9	10	7.2
Magnetic Sail	5	4	3	4	5	9	5
Space-based Magnetic Field Generator	2	10	2	1	1	1	2.8

Elimination Technology Rating Explanation

	Practicality	Scalability	Affordability Development	Affordability Construction	Affordability Implementation	Affordability Operation
1	Nearly impossible	Could not adapt to a change in the debris environment	Idea has been proposed, no research has been done on it or similar technologies	Cost prohibitive	Rebuild everything	Reinvest 100% per year
2		Can adapt to minor growth in the debris environment				
3						
4		Can adapt to moderate growth of the debris environment	A formal study has of the technology has been conducted			
5	Will work but will have little impact				Build something new	Reinvest 50% per year
6		Can adapt to a significant growth in debris, but has an exponential cost model				
7				Funding requires additional spending		
8		Can adapt to significant debris changes with a linear cost model	Individual components have been tested, but the complete system has not			
9						
10	Will work and will have desired impact	Technology can adapt to any change in debris environment without increasing cost	Deployable without any additional research necessary	Can be funded with no impact to budgetary spending	Modify current equipment	No annual investment

Appendix H – Orion Study Laser Removal Options

Proposed System	**Demonstration**		**System A**		**System B**		
Description	This is designed to test the system using existing hardware and technologies		Clear out 200-800 km altitude within 3 years of approval		Options for Advanced Technology System (using Near-Term Technologies) Clear out 200-1500 km within 3 years of approval		
System Component	**Option 1**	**Option 2**	**Option 1**	**Option 2**	**Option 1**	**Option 2**	**Option 3**
Target Set Altitude Type	Up to 300 km Special demo targets (shuttle deployed)	Up to 300 km Special demo targets (shuttle deployed)	Up to 800 km existing debris	Up to 800 km existing debris	Up to 1500 km existing debris	Up to 1500 km existing debris	Up to 1500 km existing debris
Laser	1-10ns pulsed NdYag (100J)	1-10ns pulsed NdYag (100J)	5 ns pulsed NdYag (5 KJ, 1-5Hz)	5 ns pulsed NdYag (5 KJ, 1-5Hz)	100 ps repped-pulse pulsed NdYag (2-4KJ cooled, 1-5Hz) (requires demonstration)	10 ps repped-pulse pulsed NdYag (10-20KJ cooled, 1-5Hz)	CW Iodine (2-4 MW, ground-based, recycled gas)
Estimated Cost	1.3-3.0	1.3-3.0	28.6-31.6	33.3-37.3	45.9-66.0	50.9-79.9	67.9-105.9
Acquisition/Tracking	Passive Electro-Optical (STARFIRE- 4 h/day operation at night)	Radar (Haystack-24 h/day operation)	Passive Electro-Optical (STARFIRE- 4 h/day operation at night)	Radar (Haystack-24 h/day operation) against real debris targets	Microwave radar; remote or located near Pusher site (24h/day operation)	Pusher Laser as active illuminator and ranging radar (24h/day operation)	Pusher Laser as active illuminator and ranging radar (24h/day operation)
Cost (in millions)*	13-23	16-28	57-69	93-108	140-176	145-195	172-239

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About the Internship Program

This report was compiled by six University of Nebraska at Omaha students from August – December 2007. As project interns employed by the U.S. government through USSTRATCOM, they worked at the Global Innovation and Strategy Center (GISC) in Omaha, Nebraska, about 12-20 hours per week. They were restricted to a commercial network to research space debris prevention and elimination technologies and associated policy issues. Periodic progress briefings were presented to GISC employees during the duration of the project. The final briefing was presented numerous times to USSTRATCOM and other government employees, academia, and the private sector.

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Jared Brower is currently enrolled at the University of Nebraska at Omaha pursuing dual Bachelor degrees in Computer Science and Management Information Systems with a concentration in Information Assurance and a minor in Mathematics. Jared's primary focus for the project was ground-based lasers and information sharing.

Stephanie M. Cook graduated from the University of Nebraska at Omaha with a Bachelor of Science in Political Science and she is currently a Master's candidate in the Political Science 18:18 program. Stephanie is a graduate teaching assistant in English 1160 with The Goodrich Program at UNO. Stephanie Cook's primary focus for the project was international policy analysis.

Edward James Dale is currently enrolled at the University of Nebraska at Omaha. He is pursuing a Bachelor degree in Electronic Engineering with a minor in mathematics. Edward's primary focus for the project was evaluating all existing technologies and determining how they can be used to eliminate space debris.

Josh Koch is currently enrolled at the University of Nebraska at Omaha. He is pursuing a Bachelor degree in Physics and Mathematics. Josh's primary focus for the project was prevention methods.

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